THE EFFECT OF CYCLIC FORCES UPON FINGER JOINTS WITH IMPAIRED RANGES OF MOTION

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I certify that this thesis is the true and accurate version of the thesis approved by the examiners.

Signed ....[redacted].... Date ...15 June 1999...
Dr John R Thorpe (Director of Studies)

CONTENTS

CHAPTER 3

OVERVIEW OF FINGER JOINT BIOMECHANICS AND PATHOMECHANICS WITH REFERENCE TO CONTINUOUS PASSIVE MOTION THERAPY

CHAPTER 4

REVIEW OF THE APPLICATION OF CONTINUOUS PASSIVE MOTION TO THE HAND

CHAPTER 5
EXPERIMENTAL EQUIPMENT

CHAPTER 6
EXPERIMENTAL METHOD, DATA COLLECTION AND PROCESS OF DATA

CHAPTER 7
ANALYSIS AND RESULTS

CHAPTER 8
CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS FOR FUTURE WORK

APPENDICES

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The illustrations of orthoses were taken from 'Biomechanical Basis of Orthotic Management' (Butterworth-Heinemann Ltd) and the anatomical illustrations were taken from 'The Anatomy and Mechanics of the Human Hand' by Taylor CL and Schwarz RJ.

Mr Rod Moore of Medical Dynamics (Chorley, Lancashire) kindly gave me his opinions on the current obstacles which limit clinical use of hand CPM machines which I have summarised in section 4.6.

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ABSTRACT

The two aims of this research programme were;

(1) To study the effects of the application of continuous passive motion (CPM) upon finger joints with limited range of motion (ROM).

(2) To investigate the development of a prototype CPM machine for hand rehabilitation after flexor tendon repairs.

The principal results of the research were;

(1) Tests upon patients using purpose-built instrumented machines, performed in order to obtain data on the magnitudes and nature of the forces exerted during CPM therapy, revealed that the force magnitudes were surprisingly high. Tensile forces (pulling fingers into flexion) and compressive forces (pushing fingers into extension) of 15 and 10 Newtons respectively were recorded though typical maximum forces were 7 and 6 Newtons.

(2) The trends observed in the force data were neither dramatic nor consistent. In part, this was caused by active finger movements, coupling effects between adjacent fingers and by some slight slippage of the machine's attachment rod on the fingers.

(3) Gains in the range of finger joint range of motion (ROM), were consistently obtained during CPM treatment, but were rarely retained in the non-CPM periods.

(4) The practical problem of preventing the slippage of the CPM machine's attachment rod on the fingers could be minimised by the application of a linkage, which was developed during the research programme. This linkage has the further benefit that it can be used to mobilise finger joints in a selective manner. The linkage was satisfactorily tested and is regarded as a significant contribution to orthotic design. Further research will be necessary to demonstrate the effectiveness of the linkage for patients who require hand rehabilitation after flexor tendon repairs.

(5) A control group of patients with Dupuytren's contractures was studied to find the time needed for the return of function when CPM is *not* applied. Using the assumption that hand strength is related to functional recovery (because of dispersal of oedema), it was found that recovery takes eight weeks. It was reasoned that, in the general case, CPM should be applied for eight weeks after surgery or injury.

LIST OF PHOTOGRAPHS, FIGURES and TABLES

Photographs

Figures

Tables

CHAPTER 1

INTRODUCTION

1.1 Background

A normal hand possesses remarkable dexterity for prehensile activities. The consequences of impaired hand function upon social activities and employment can be devastating and a major aspect of hand rehabilitation is concerned with the preservation or restoration of function.

Hand rehabilitation methods include the manipulation of joints by external means in order to increase joint range of motion, promote healing, disperse oedema and clear haemarthroses. Manipulation can be achieved by physiotherapy, occupational therapy, orthoses (splintage) and therapy machines. In recent years, there has been interest in the application of motorised therapy machines, largely because of the pioneering work of Professor Salter of Toronto University, who investigated the effect of continuously and passively moving joints in a slow, repetitive and cyclic manner. He coined the phrase *"continuous passive motion"* to describe this type of motorised treatment and established a sound incontrovertible body of evidence to support the concept of its use. He has reported its benefits on the healing of cartilage (Salter *et al* 1980, 1982, 1989), intra-articular fracture models (Salter *et al* 1979), acutely septic joints (Salter *et al* 1981) and on disorders and injuries of synovial joints (Salter *et al*, 1984).

Treatment by continuous passive motion is widely accepted and is often referred to by its abbreviation '*CPM*'. It is applied mostly for knee rehabilitation and there have been disappointingly few controlled trials and objective studies of its application to the hand. It was presumed correctly at the beginning of this research programme that there were significant problems associated with the application of CPM machines to the hand. These problems are largely technical; it is extraordinary difficult to develop a machine which is acceptable to its prescribers in terms of meeting clinical objectives and also acceptable to its users in terms of ease of application and comfort. Furthermore, it is difficult to quantify the effects of CPM upon hand function because function involves multiple factors such as joint range of motion, strength, sensation and sensibility, not all of which can be measured objectively. Studies into hand rehabilitation techniques frequently run into difficulties of obtaining reliable and repeatable data.

1.2 Rationale for the research programme

The overriding impetus for this research was the desire to develop a CPM machine for the rehabilitation of zone II flexor tendon repairs. It was recognised that this could not be achieved unless knowledge and experience were acquired to provide a better understanding of the difficulties of applying CPM machines to fingers and the role of CPM upon finger joints which have some limitation in range of motion, a situation which is likely to occur after hand surgery. Leading from this initial investigation would be the opportunity to develop a prototype CPM machine for the rehabilitation of patients who have undergone flexor tendon repair. It was therefore decided that the research programme should have two stages of investigation which are described below.

1.2.1 Investigation into the application of CPM upon stiff finger joints

Problems with metacarpophalangeal (MCP) and interphalangeal (IP) joints may be caused by a multitude of reasons but whatever the cause, the major complication may be a joint which has limited range of motion, frequently accompanied by pain and swelling. Acute stiffness occurs after many types of trauma or surgery and in the majority of cases is temporary though it has been recognised for a long time that the earlier the patient is started on a structured rehabilitation programme, the better are the chances of avoiding complications (Adamson, 1970). The predominant rehabilitation regimes involve joint manipulation by conventional therapy and orthoses. Experience of treatment by CPM is limited, a fact which is evident from the published data.

1.2.2 Investigation into the development of a CPM machine for the rehabilitation of zone II flexor tendon repairs

The management of zone II flexor tendon repairs is a severe rehabilitation challenge because of the risk of adhesions forming between a repaired tendon and its sheath. The current technique to prevent adhesions is to move finger joints, and hence the tendons within their sheaths, by active finger extension against an elastic band. The rested finger is held flexed by an elastic band running between the finger nail and the flexor surface of the distal forearm (possibly via a pulley) until it is actively extended against the resistance of the elastic band. This returns the finger to the flexed position, avoiding tension on the repair flexor tendon. This method was advocated by Lister *et al* (1977) and Lister (1984, 1985) and is now widely used. Flexion contracture of the proximal interphalangeal (PIP) joint has proved to be a troublesome complication of elastic band mobilisation and is the chief disadvantage of the technique. Full extension of the interphalangeal joints during rehabilitation is considered essential. Lister *et al* (1977) have stated that 'failure to do so will result in a disastrous flexion contracture and will compromise any subsequent attempt at salvage by secondary tendon surgery'.

According to Burge and Brown (1990), there are four predominant factors which may cause flexion deformity of the PIP joint:

- the contour of the dorsal splint may not provide sufficient clearance for full extension of the PIP joint
- the finger extensors are unable to extend an elastic band which is too short or too stiff
- patients may not appreciate the importance of full extension or fail to exercise the finger as intended
- active extension may be weakened by intrinsic muscle injury or paralysis.

It is realised that motorised CPM therapy may overcome these problems if a suitable machine could be developed. The first two problems would be addressed during the design of the machine; the third and fourth could be overcome by the application of external power.

1.3 Aims of the research programme

This research programme had two specific aims which were;

- to study the effect of CPM upon finger joints with limited range of motion (ROM);
- to investigate the development of a prototype CPM machine for the rehabilitation of flexor tendon repairs

The achievement of the second aim would require the use of the practical knowledge and experience gained in achieving the first aim.

CHAPTER 2

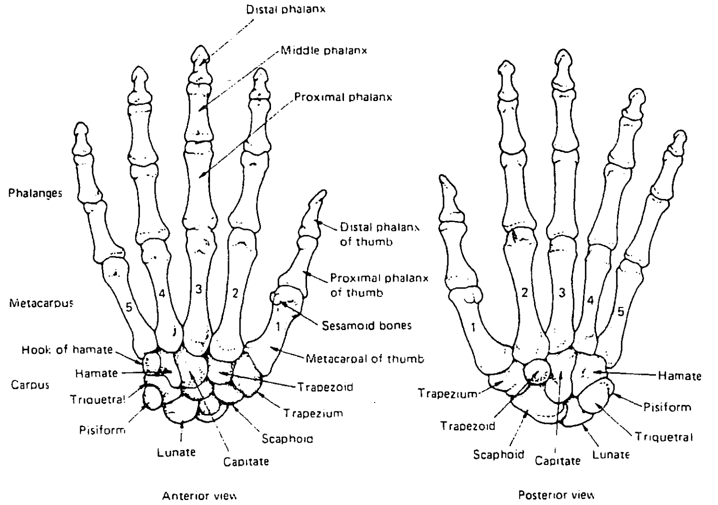
HAND ANATOMY AND THE CAUSES AND TREATMENT OF FINGER JOINT CONTRACTIONS

2.1 Hand anatomy

This section has been included to provide a description of hand anatomy, to assist understanding of the principles of orthotic management. The information has been taken from standard anatomical textbooks, ('Cunningham's Manual of Practical Anatomy', G. Romanes, & 'The Anatomy and Mechanics of the Human Hand', C.L. Taylor & R.J. Schwarz).

2.1.1 Bones in the wrist, hand and fingers

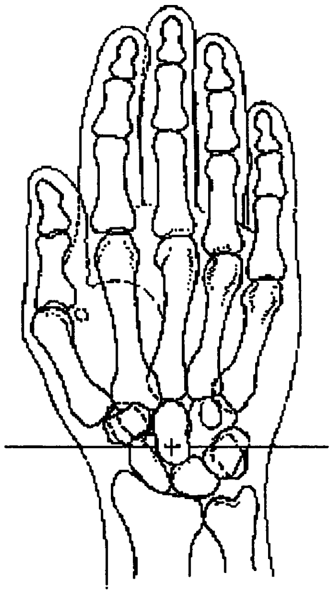
The distal ends of the radius and ulna articulate with the carpus. The carpus contains eight bones which are approximately grouped into two rows; the distal row contains the trapezium, trapezoid, capitate and hamate bones and the proximal contains the scaphoid, lunate, triquetral and pisiform bones. The palm of the hand contains metacarpals for each digit. The four fingers have proximal, middle and distal phalanges whereas the thumb has only a proximal and distal phalanx - the middle phalanx was 'lost' during man's evolution. Sesamoid bones may be present at the distal interphalangeal and metacarpophalangeal joints (Kohler, 1968).



Bones of the wrist and hand
figure 2.1

2.1.2 The joints in the wrist, fingers and thumb

The wrist bones are arched to form a palmar tunnel through which pass the long finger flexor tendons. This groove is covered by the tough transverse flexor retinaculum whose function is to protect the underlying soft tissues and also to act as a pulley for the flexor tendons when the wrist is flexed. The wrist bones have minimal relative movement with respect to one another. Youm and Yoon (1979) have shown that the centres of rotation of the wrist joint are located in the capitate (figure 2.2).



Centre of rotation of the wrist
figure 2.2

The ranges of normal wrist motion, described by Bird and Stowe (1982), are given in table 2.1

Movement	*Age:* *0 - 19*	*20 - 29*	*30 - 39*	*40 - 49*	*50 - 80 +*
Flexion	85.3	75.7	85.2	81.5	81.2
Extension	55.1	48.9	51.3	45.9	44.2
Abduction	37.1	30.5	33.4	27.1	28.8
Adduction	25.6	20.9	24.2	22.1	23.3

Ranges of active motion at the wrist (Bird and Stowe, 1982)
table 2.1

The proximal ends of the second and third metacarpals are rigidly connected to the trapezoid and capitate. As a result, these two metacarpals and the carpal bones act as a single rigid segment. The fourth and fifth metacarpals have some limited flexion movement with respect to the hamate. The fourth metacarpal is able to flex 10 - 15 degrees at the carpometacarpal joint and the fifth metacarpal can flex 20 - 30 degrees. These movements are small but are particularly important in providing maximum palm skin contact area for grasp activities. The head of each metacarpal is unicondylar and this allows motion of the proximal phalanx in the planes of flexion/extension and abduction/adduction. The proximal phalanx can rotate about its longitudinal axis on the metacarpal head but the strong capsular ligaments limit this movement. The metacarpophalangeal joint is similar in shape to a 'ball and socket'. The articular heads of the proximal and middle phalanges are bicondylar. The articular surfaces of the interphalangeal joints are congruent so they act as simple hinges and these joints can be likened to a 'tongue and groove'. Table 2.2 lists the maximum ranges of movement of the metacarpophalangeal joints according to Batmanabane and Malathi (1985).

Movement	*index*	*middle*	*ring*	*little*
Flexion	70	90	90	95
Extension	depends upon joint laxity			

Ranges of motion at the metacarpophalangeal joints from the neutral position (Batmanabane and Malathi, 1985)
Table 2.2

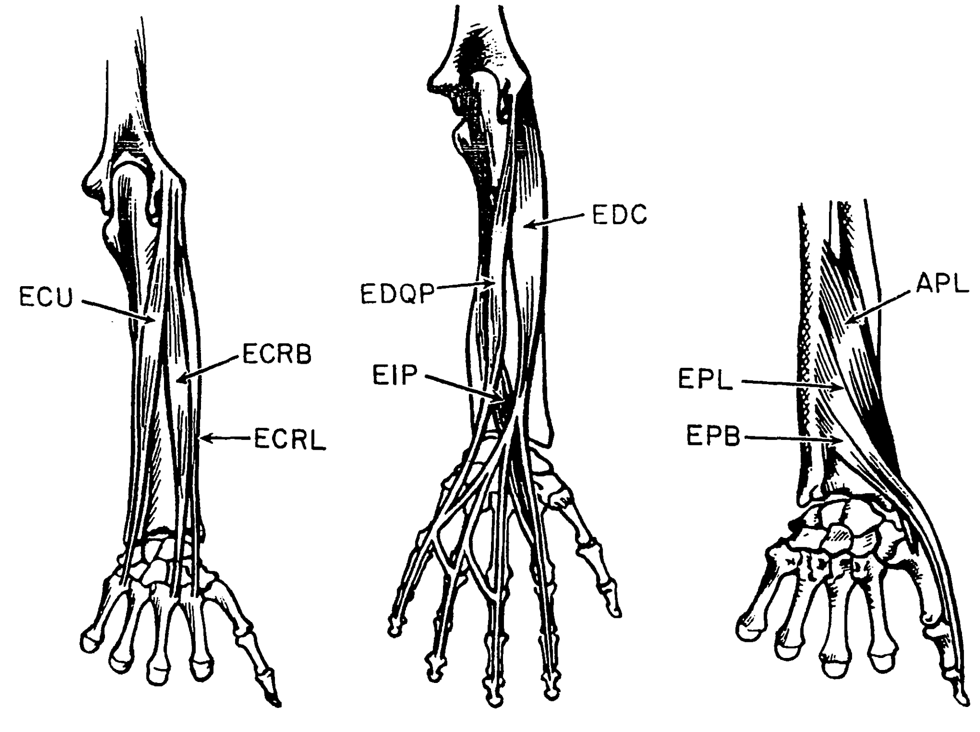
The ranges of movement of the interphalangeal joints are typically 100 - 110 degrees for the proximal joint and 90 degrees for the distal joint, according to the American Academy of Orthopaedic Surgeons (AAOS). Wide variations in extension angles occur and these are caused by the extent of joint laxity. Measurements are from the neutral position with the fingers in the plane of the hand.

2.1.3 Musculature

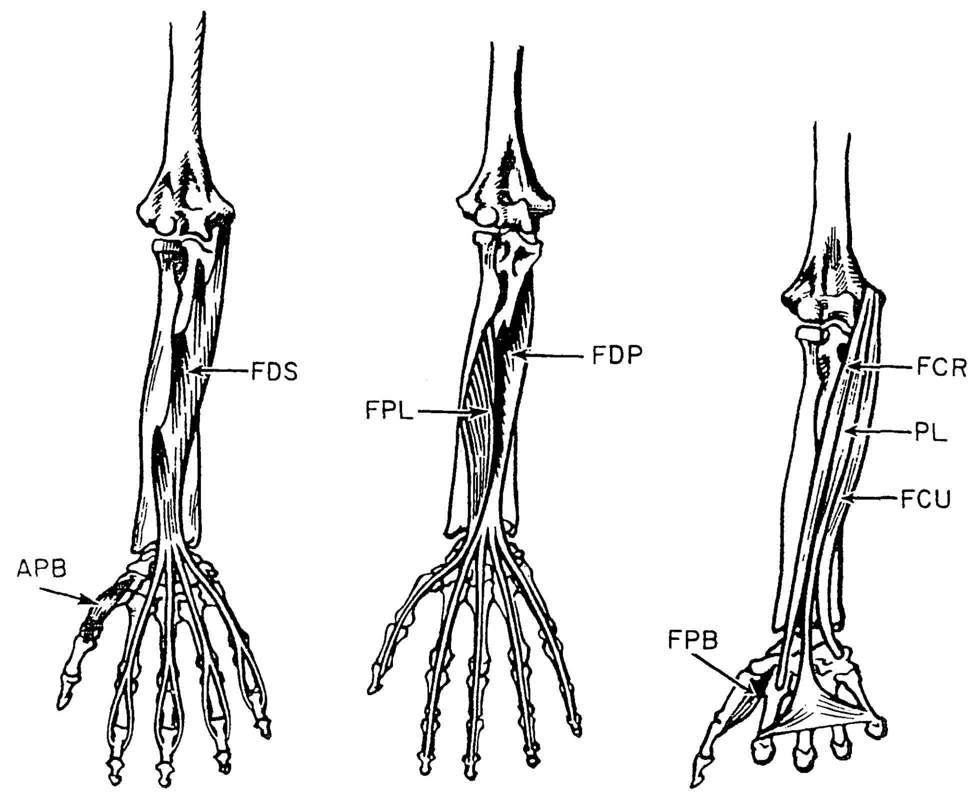
2.1.3.1 The wrist and palm

Pure wrist extension is provided by the extensor carpi radialis brevis; combined flexion and adduction by the flexor carpi ulnaris; combined extension and adduction by the extensor carpi ulnaris; and combined extension and abduction is provided by the extensor carpi radialis longus (figures 2.3 & 2.4). Wrist supination is provided by the supinator and bicep muscles, and pronation by the pronator quadratus and pronator teres muscles.

When the fingers are extended, the distal ends of the finger metacarpals lie in a flat plane, but they form a concave palmar arch when the fingers are flexed to grasp an object. The palm has four compartments. The thenar and hypothenar compartments are enclosed in their own layers of fascia and each contains the short muscles for the thumb and little finger respectively. The intermediate compartment contains the long finger flexor tendons, the lumbricals and most of the blood vessels and nerves. Finally, the adductor compartment contains the adductor pollicis.



Wrist and finger extensors
figure 2.3



Wrist and finger flexors
figure 2.4

APL abductor pollicis longus
ECU extensor carpi ulnaris
ECRB extensor carpi radialis brevis
ECRL extensor carpi radialis longus
EDC extensor digitorum communis
EDQP extensor digiti quinti proprius
EIP extensor pollicis brevis
EPB extensor pollicis brevis
EPL extensor pollicis longus

The vulnerable tendons, lumbricals, blood vessels and nerves, located in the intermediate compartment in the middle of the palm, are protected by the tough palmar aponeurosis. This is a strong fibrous sheet which is composed of strong longitudinal fibres mixed with transverse fibres which bind them together. The tissue is triangular in shape; the deep fibres in its proximal apex fuse with the flexor retinaculum, and its distal end divides into four processes, which in turn divide into two slips which fuse with the deep fascia on the back of the digits and with the strong deep transverse ligaments of the palm. The palmar aponeurosis has particular relevance in orthotic management, because it is affected by Dupuytren's disease.

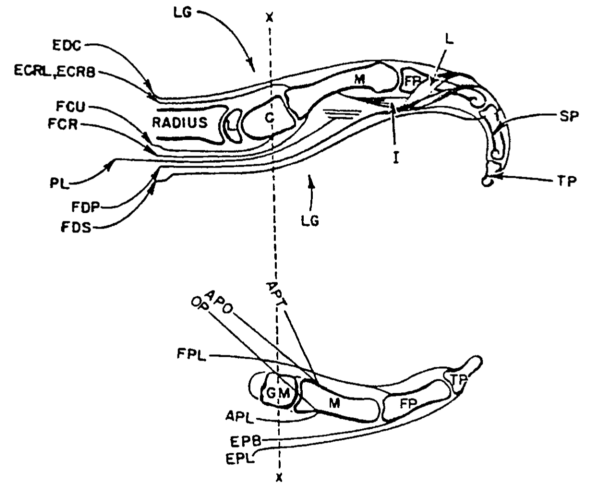
2.1.3.2 The fingers

Finger flexion and extension occur through the action of the extrinsic muscles located in the forearm, and intrinsic muscles located in the hand (figure 2.5). The intrinsic muscles also have a role in finger abduction and adduction. These muscles are considered in turn.

Extrinsic Flexor Muscles

The extrinsic flexor muscles comprise the flexor digitorum sublimis and flexor digitorum profundus. The tendon of the flexor digitorum sublimis is inserted into the finger's middle phalanx whereas the tendon of the deeper flexor digitorum profundus is inserted into the distal phalanx. The sublimis tendon is more superficial than the profundus tendon over the metacarpal and proximal half of the first phalanx. It is therefore inevitable that the two tendons must cross one another before their insertion points. This is achieved by bifurcation of the sublimis tendon in order that the profundus may pass through at the level of the metacarpophalangeal joint. The bifurcations wrap around the profundus tendon, reuniting at the proximal interphalangeal joint, proximal to the insertions into the sides of the middle phalanx. The flexor digitorum sublimis muscle flexes the proximal interphalangeal joint and the angle of contact of the tendon with the middle phalanx increases with increasing flexion of the proximal interphalangeal joint. This muscle is a weak flexor of the metacarpo-phalangeal joint but only when the proximal interphalangeal joint is fully flexed.

The flexor digitorum profundus flexes the distal interphalangeal joint. However, when the proximal interphalangeal and metacarpophalangeal joints are passively flexed to ninety degrees, the profundus tendon becomes too slack for functional use. It is also a weak flexor of the proximal interphalangeal and metacarpophalangeal joints but only when the distal interphalangeal joint is fully flexed.



schematic sectional view through the thumb and middle finger
figure 2.5

LG indicates presence of ligamentous guides which channel close to the wrist the tendons of muscles originating in the forearm
XX indicates relative position of carpal bases of the thumb and fingers flexor digitorum sublimis

APL	abductor pollicis longus	FDP	flexor digitorum profundus
APO	adductor pollicis obliquus	FDS	flexor digitorum sublimis
APT	adductor pollicis transversus	FP	first pahalanx
C	capitate	FPL	flexor pollicis longus
ECRB	extensor carpi radialis brevis	GM	greater multangular
ECRL	extensor carpi radialis longus	I	interosseus
EDC	extensor digitorum communis	M	metacarpal
EPB	extensor pollicis brevis	OP	opponens pollicis
EPL	extensor pollicis longus	PL	palmaris longus
FCR	flexor carpi radialis	SP	second phalanx
FCU	flexor carpi ulnaris	TP	third phalanx

Extrinsic Extensor Muscles

These comprise the extensor digitorum communis, the extensor indicis (for the index finger only) and the extensor digiti minimi (for the little finger only).

The tendon of the extensor digitorum communis initially develops into the extensor expansion in the region of the metacarpophalangeal joint, before insertion into the proximal phalanx to provide extension of the metacarpophalangeal joint. After the extensor expansion, the extensor digitorum communis trifurcates at the distal end of the proximal phalanx. Its middle portion develops into the median band which is inserted into the proximal end of the middle phalanx and acts as an extensor for the proximal inter-phalangeal joint. The two lateral bands are inserted into the proximal end of the distal phalanx and hence act as extensors for the distal interphalangeal joint. The principal role of the extensor digitorum communis is extension of the metacarpophalangeal joint which occurs in all positions of the wrist. The extensor indicis and extensor digiti minimi have deep insertions in the extensor digitorum communis tendons for the index and little fingers respectively. Their function is the same as the extensor digitorum but they have the secondary role of extending the index and little fingers individually.

Intrinsic Muscles

The intrinsic muscles comprise the lumbricals whose function is both flexion and extension of finger joints, and the interossei whose function is abduction and adduction of the fingers (figure 2.6). The little finger has intrinsic muscles in the hypothenar eminence. These are the abductor digiti minimi (abductor digiti quinti), flexor digiti minimi (flexor digiti quinti brevis) and opponens digiti minimi (opponens digiti quinti).

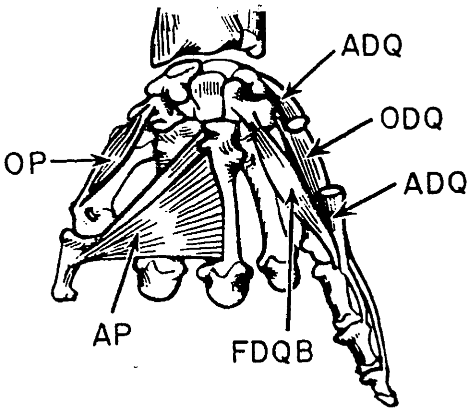
Each of the four lumbricals flexes the metacarpophalangeal joint and also extends the proximal and distal interphalangeal joints because it is inserted into the extensor tendon. There are four palmar and four dorsal interosseous muscles. The palmar interossei adduct the fingers towards the middle finger. Additionally, each flexes the metacarpophalangeal joint and extends the interphalangeal joints. The dorsal interossei abduct the fingers. The first and fourth abduct the index and ring fingers from the middle one. The second abducts the middle finger towards the index and the third adducts it towards its former position and, continuing to act, abducts it towards the ring finger. The second dorsal interosseous then restores it to its former position. Each dorsal interosseous flexes the metacarpophalangeal joint and extends the interphalangeal joints in a similar manner to the palmar interossei.

The abductor digiti minimi abducts and slightly flexes the little finger. The opponens digiti minimi draws the fifth metacarpal slightly forward and turns it towards the radial side.

Each finger, therefore, is provided with an adductor and an abductor. The index, middle and ring fingers each have two interossei. The little has its own abductor and the fourth palmar interosseous as an adductor.

Intrinsic muscles of the hand
figure 2.6

ADQ abductor digiti quinti
AP adductor pollicis
FDQB flexor digiti quinti brevis
ODQ opponens digiti quinti
OP opponens pollicis



2.1.3.3 The thumb

The unique function of the thumb is achieved through its four extrinsic and five intrinsic muscles.

Extrinsic Muscles

These comprise the abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus and flexor pollicis longus. The abductor pollicis longus abducts the thumb metacarpal. It also flexes the metacarpal due to the fact that the abductor tendon passes anteriorly to the extensor pollicis brevis and extensor pollicis longus. The extensor pollicis brevis has two roles; first, it extends the metacarpophalangeal joint and second, it moves the first metacarpal laterally. It abducts the thumb if the wrist is stabilised by synergistic action of the flexor carpi ulnaris and particularly the extensor carpi ulnaris. If synergistic action is not provided, the extensor pollicis brevis abducts the wrist. The action of the extensor pollicis longus is extension of both the proximal interphalangeal and metacarpophalangeal joints. It also moves the metacarpal medially and posteriorly. The flexor pollicis longus flexes the interphalangeal joint and secondarily, flexes the metacarpophalangeal joint.

Intrinsic Muscles

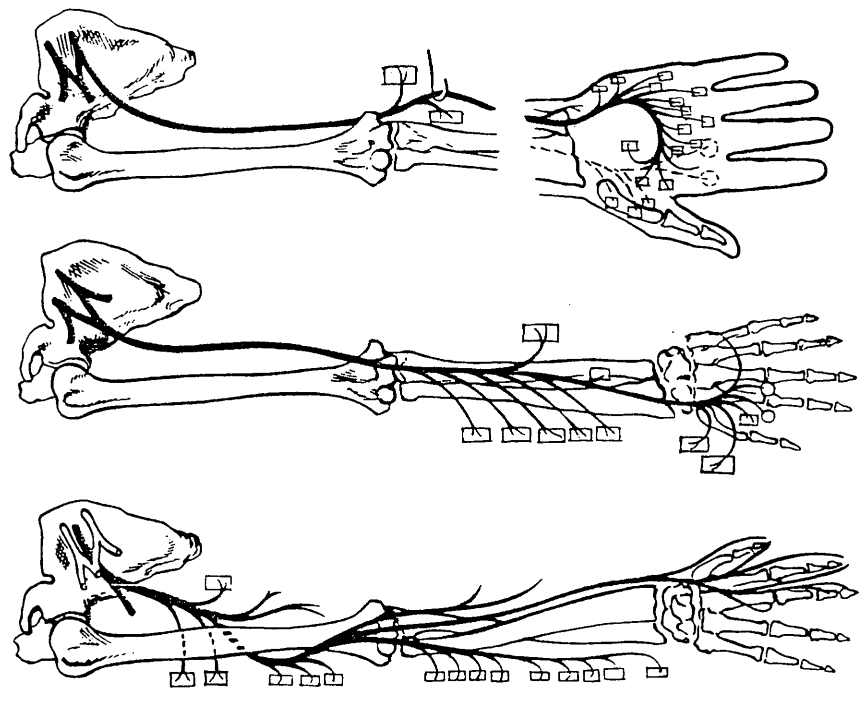
The five intrinsic thumb muscles are divided into two groups. The lateral group comprises the flexor pollicis brevis, opponens pollicis and abductor pollicis brevis and is collectively known as the thenar eminence. The medial group comprises the two heads of the adductor pollicis. The flexor pollicis brevis flexes the metacarpophalangeal and proximal interphalangeal joints. The opponens pollicis flexes the metacarpophalangeal joint and rotates the metacarpal medially. The abductor pollicis brevis abducts the thumb at the carpometacarpal joint and slightly flexes the proximal phalanx. The adductor pollicis adducts the thumb's metacarpal towards the palm.

2.1.4 Nerve supply

The three main nerves of the forearm and hand are the ulnar, radial and median. They are so named according to their relative positions in the forearm (figure 2.7).

The ulnar nerve passes superficially over the flexor retinaculum to enter the palm. It runs on the lateral side of the pisiform bone and its superficial branch in the hand passes in front of the hook of the hamate. Its roots are C7, C8 and T1. The ulnar nerve supplies the flexor carpi ulnaris, flexor digitorum profundus (medial half), palmaris brevis, all eight interossei, adductor pollicis, two medial lumbricals, abductor digiti minimi, flexor digiti minimi and opponens digiti minimi. The palmar cutaneous branch of the ulnar nerve supplies the skin of the inner side of the palm. The dorsal cutaneous branch supplies the skin on the ulnar side of the little finger and adjacent sides of the little and ring fingers. The superficial branch in the palm supplies cutaneous branches to the little finger and ulnar side of the ring finger. The dorsal cutaneous branches come off 8 - 10 centimetres above the wrist. If the ulnar nerve is cut at the wrist, the dorsal branch escapes and the skin sensation on the back of the hand is unaffected.

The radial nerve leads to the posterior interosseous nerve which breaks into many branches which makes repair of any injury difficult. Its roots are C5, C6, C7, C8 and T1. It is distributed to all muscles on the back of the forearm except anconeus. The posterior interosseous nerve supplies the extensor carpi radialis brevis, supinator, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus and extensor indicis. The radial nerve divides into two branches. The lateral branch supplies the skin on the outer aspect of the thumb. The medial branch supplies the adjacent sides of the thumb, index, middle and ring fingers. The radial nerve supplies the back of the fingers with the exception of the distal phalanx of the thumb and the middle and distal phalanges of the fingers which are supplied by the median and ulnar nerves.



Nerves supply for the hand

Top – ulnar nerve *middle – median nerve* *bottom – radial nerve*

Figure 2.7

The median nerve runs down the middle of the forearm between the superficial flexors of the fingers (flexor digitorum superficialis) and the deep flexors (flexor digitorum profundus). Its roots are C5, C6, C7, C8 and T1. At the wrist, it lies between the tendons of the flexor carpi radialis and palmaris longus and is superficial. It then passes deep to the flexor retinaculum with the flexor synovial sheaths and breaks into its medial and lateral divisions. The median nerve and its anterior interosseous branch supply all the muscles on the front of the forearm with the exception of the flexor carpi ulnaris and the lateral part of the flexor profundus. The lateral division of the median nerve in the palm supplies the abductor pollicis, flexor pollicis brevis and opponens pollicis. The medial division in the palm supplies the lateral two lumbricals, the skin over the palmar aspect of the hand from the thumb to the ring finger, and the skin over the dorsal aspect of the distal phalanx of the thumb, index and middle fingers. The median nerve thus supplies all the muscles of the hand lateral to the tendon of flexor pollicis longus and the skin of the central part of the central part of the palm, the dorsal aspect of the distal phalanx of the thumb, and the two distal phalanges of the index, middle and lateral half of the ring finger.

2.1.5 Blood supply to the hand and fingers

The brachial artery in the upper limb divides into the radial artery which runs down the lateral side of the forearm, and the ulnar artery which runs down the medial side. Both arteries enter the palm and give off branches which pass towards the digits. The radial artery supplies the main vessel of the thumb and to a large branch of the radial side of the index finger. The ulnar artery ends by joining branches of the radial to form the superficial and deep palmar arches. The superficial palmar arch supplies most of the blood to the hand. The three or four common palmar digital arteries that arise from the superficial palmar arch course through the palm. Opposite the webbing of the fingers, they give rise to the digital arteries supplying both sides of the fingers.

The digital arteries are contained with the digital nerves in the neurovascular bundles, which lie against the sides of the fibrous flexor sheaths and are enclosed in the digital ligaments. The digits are drained of venous blood through anastomosing palmar and dorsal digital veins. The blood from the digits and the palm thus drains to the dorsal venous network on the back of the hand.

2.2 Current orthotic treatment methods for the wrist, fingers and thumb

The ultimate aim of a wrist hand orthosis is to improve or maintain function, but the patient may consider the orthosis to be a hindrance when it is first applied, especially those types which are prescribed to be used during periods of tissue healing. Experience has shown that there is a fine balance between improving function in one part of the limb and restricting function in another part. Considerable expertise is required to apply wrist hand orthoses successfully.

Although this research programme was concerned with the application of *CPM* machines for the treatment of finger contractions, these may occur in conjunction with contractions at the wrist and thumb joints so it is necessary to consider the orthotic treatment of the latter also.

2.2.1 Incidence of hand injuries

The upper limbs suffer a high incidence of injury such as lacerations, fractures, burns and crushing injuries. The joints of the wrist, hand and fingers are particularly susceptible to the development of contractures and deformities due to the number and close proximity of the joints and proliferation of soft tissues.

A review of one year's supply of wrist hand orthoses in Dundee (McDougall *et al*, 1985) revealed that the clinical indications for prescription were as follows:

traumatic injuries	61%
hemiplegia (typically CVA)	17%
relief of wrist pain	13%
Dupuytren's contracture	9%

Within the group of traumatic injuries, the principal pathologies for prescriptions were in the following proportions:

tendon injuries	39%
joint injuries	34%
nerve injuries	27%

These injuries may occur together. It is considered that the figures above represent a typical spectrum for a European city. Variations can be expected for hospitals with specialist facilities for the treatment of patients with rheumatoid arthritis.

2.2.2 Clinical objectives and biomechanical requirements of orthotic management

The maintenance of joint mobility and prevention of deformity or contracture are the most important functions of wrist hand orthoses (Muckart, 1970). The principal objectives when using an wrist hand orthosis are to maintain normal joint alignment in the absence of contractures, or to return affected joints to their normal physiological positions when contractures are present. When patients have reduced muscle power or muscle imbalance, orthoses may be used to either hold joints in their position of function or to provide assistance to dynamic motion. Orthoses may also be used to immobilise joints to provide functional stability or to prevent painful motion which may occur in osteoarthritis or rheumatoid arthritis.

The design of orthoses for the wrist and hand is particularly difficult for three reasons. First, the lengths of finger and thumb bones are particularly short for the development of moments. This has the disadvantage that the short force lever arms about finger and thumb joints must be compensated for by proportionately greater magnitudes of applied force in order to generate the desired corrective moments. Second, the wrist and hand contain a large number of anatomical joints which may require orthotic management. Third, orthotic prescriptions often require patients to be able to move their joints whilst orthoses are worn. These latter two factors considerably influence the biomechanical design of orthoses and are considered in turn below.

2.2.2.1 Requirements for the mobilisation of joints

The historical development of orthoses mirrored classical orthopaedic teaching, in that joint rest and immobilisation have key roles in the management of a wide variety of disorders of the musculoskeletal system. This view is enforced by patients themselves when they experience pain when moving joints. However, evidence has emerged that mechanical stress and motion have beneficial effects upon the repair of bone, tendon, ligament and cartilage. Gelberman *et al* (1982) have demonstrated that intermittent passive motion can prevent the adhesion of flexor tendon sheaths whilst tendon healing occurs. It is apparent that active mobilisation can be achieved whilst an orthosis is used, provided it is structurally flexible and easily deformed by a patient's musculature. This has led to the development of the so-called 'dynamic' or 'lively' orthoses, which can be elastically deformed with small magnitudes of energy.

2.2.2.2 Design of dynamic orthoses

The fundamental biomechanical principle governing the design of 'dynamic' orthoses is that energy is transferred from the orthosis to the tissues, and vice versa, when joint musculature is alternatively relaxed and contracted. The strain energy stored in the orthosis attempts to dissipate by placing the contracted joint tissues in a condition of mechanical stress. If the stiffness of the orthosis is increased, the amount of energy required to deform its shape is similarly increased. Flexible orthotic components must have low energy absorbing capacity and they are typically fabricated from elastic bands or coiled wire.

Historically, Bunnell's Weniger splint (1946, 1950) marked the beginning of the modern evolution of dynamic hand orthoses. His orthoses were designed to exercise and mobilise joints and at the same time, to realign joints to positions of function. His splints were enormously successful on young well-motivated World War Two casualties who were eager to return to civilian employment. The main disadvantage of his design is the fact that elastic bands can only exert force along their own longitudinal axes, whereas the finger tip actually follows a curve congruent with an equiangular spiral. The orthosis must include protruding rigid wires, which support the elastic bands, and which direct their lines of force. These 'outriggers', as they are named, make the orthosis conspicuous and they tend to hook onto clothes and bed covers. This problem was addressed by Moberg (1983) who commented that the problems associated with outriggers sometimes made their use impossible because of patients' negative reaction. He proposed the use of pulleys which would correctly direct the elastic bands' line of action and would also position the elastic bands in a longitudinal direction adjacent to the hand. A minor disadvantage of this design is the high coefficient of friction between metal and elastic, which necessitates the use of low friction rolling pulleys. Moberg's proposals have been widely accepted and his design is named the 'low-profile splint'. Variations of this design are in common use today.

An alternative method of applying strain energy from a dynamic orthosis is through the use of coiled wire. The advantages of using a coiled wire spring in preference to an elastic band are first, a spring can produce both flexion and extension moments whereas elastic bands can provide tensile force only, and second, it is inherently smaller. The disadvantage of using coiled wire is that its axis of rotation is located at its centre so it must be carefully located adjacent to the anatomical axis of rotation.

Force vector requirements

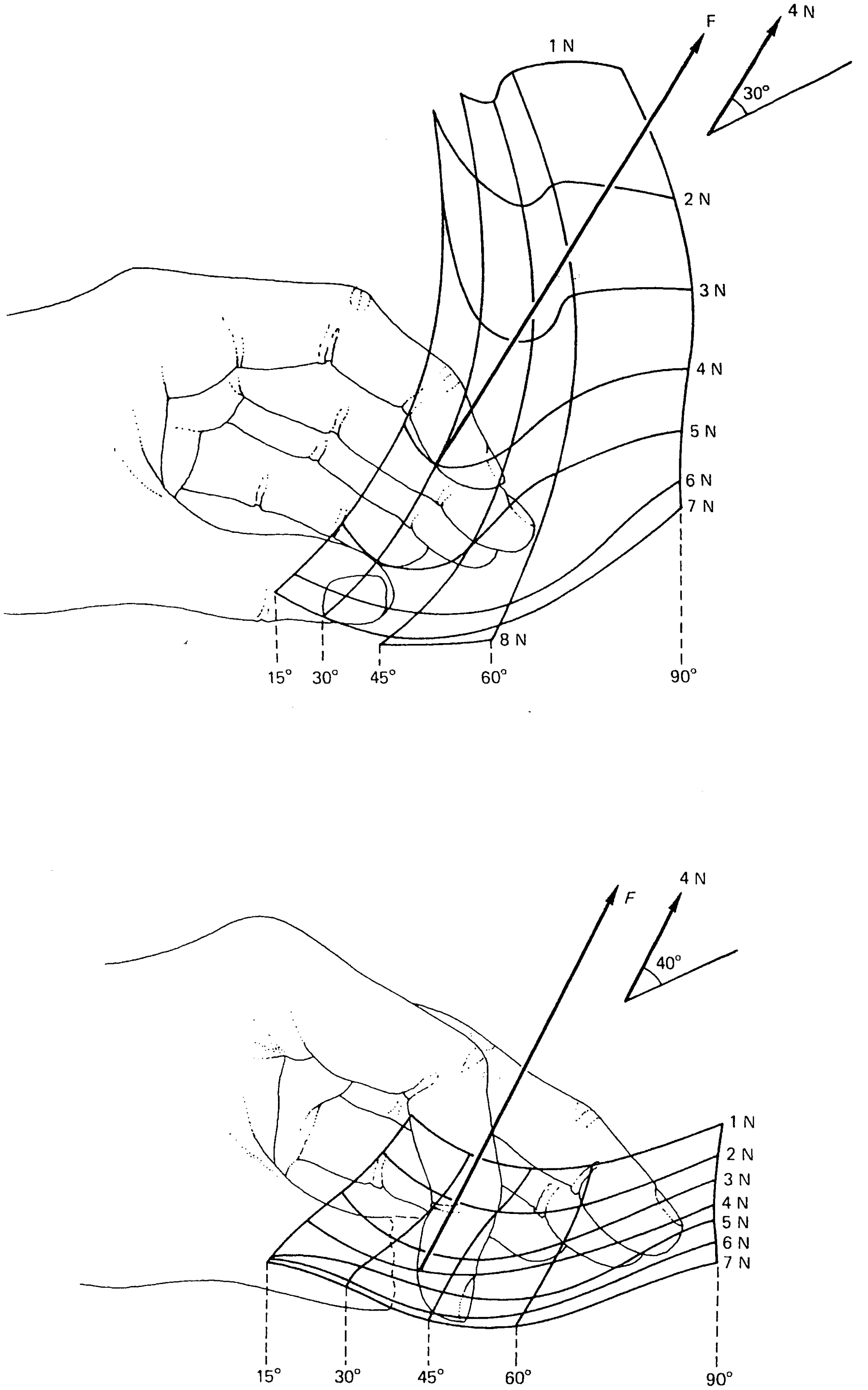
Ideally, an orthosis would provide a controlled moment upon each joint which requires corrective action. In practice, this is usually impossible due to the number of degrees of freedom involved, so the design of an orthosis may have to provide correction for multiple joints with a single force input.

The magnitude of the force exerted by a coiled wire in a dynamic orthosis should be adjusted to ensure that the magnitudes of force are tolerable to the patient. The theoretical torsional stiffness of a coiled helical spring is proportional to the modulus of elasticity of the material and the fourth power of the wire diameter, and inversely proportional to the coil diameter and the number of turns;

$$\frac{T}{\theta} = \frac{E\,d^4}{64Dn}$$

Hence, the stiffness of a particular coil is typically reduced by decreasing the wire gauge, increasing the coil diameter and increasing the number of turns in the coil.

The conditions when a dynamic orthosis could be expected to provide a satisfactory biomechanical force action are demonstrated in the following example. The illustration at the top of Figure 2.8 shows the structural properties of a dynamic finger orthosis which has been correctly fitted. The orthosis was bench tested to determine its stiffness / deformation characteristics. The dynamic component comprised a coiled wire, located on a rigid extension upon the hand interface component. The intersections on the force vector plot show both the magnitude and direction of the force vector, exerted by the dynamic orthosis, acting upon the distal phalanx. For the instance shown, the orthosis would exert a force of 4 Newtons at an inclination of 30^{O} to the longitudinal axis of the metacarpal, used as the reference axis. When the orthosis was incorrectly prepared, however, by using a spring with greater torsional stiffness, the plot shown at the bottom of figure 2.8 was produced. It can be seen that this orthosis would be unsatisfactory because the force vector is directed in too close alignment to the longitudinal axis of the distal phalanx and the coil is too stiff, witnessed by the close proximity of the force contour lines.



Structural characteristics of correctly and incorrectly fitted dynamic finger orthoses
figure 2.8

It would be impractical to quantify the stiffness / deformation characteristics of the types of coiled wire commonly used in the manufacture of orthoses because of the wide variety of possible ways they can be prepared. Instead, the orthotist/therapist has no option but to 'feel' the stiffness / deformation characteristics of an orthosis and judge its suitability.

Kinematic requirements

Orthosis design should ideally ensure that the normal motion of the interphalangeal joints is preserved. The ratio of the average angular velocities of the distal and middle phalanges, with respect to the proximal phalanx, is approximately 1.8 because flexion of the interphalangeal joints occurs during the same time period (Figure 2.9). An idealised dynamic orthosis which would, at a particular instant, provide this ratio of angular velocities is shown in figure 2.10. It comprises a coil G and a finger loop which is located on the distal phalanx and is illustrated by the kinematic offset, CDE. The three phalanges are denoted AB, BC and CD. The instantaneous centres of rotation I_{ij} are identified and a relative velocity diagram drawn.

The angular velocity of the distal phalanx with respect to the proximal phalanx is;

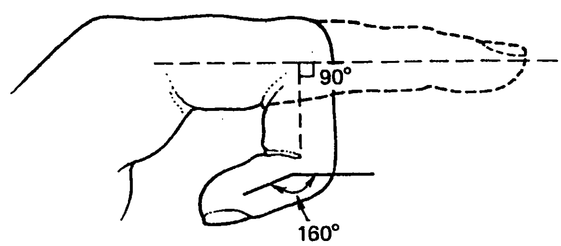
$$\frac{\text{velocity of E with respect to G}}{\text{distance between } I_{13} \text{ and E}} = \frac{g'e'}{I_{13}E} = \frac{76}{45} = 1.7$$

(from scale)

and the angular velocity of the middle phalanx with respect to the proximal phalanx is;

$$\frac{\text{velocity of C with respect to B}}{\text{distance between C and B}} = \frac{b'c'}{BC} = \frac{44}{51} = 0.9$$

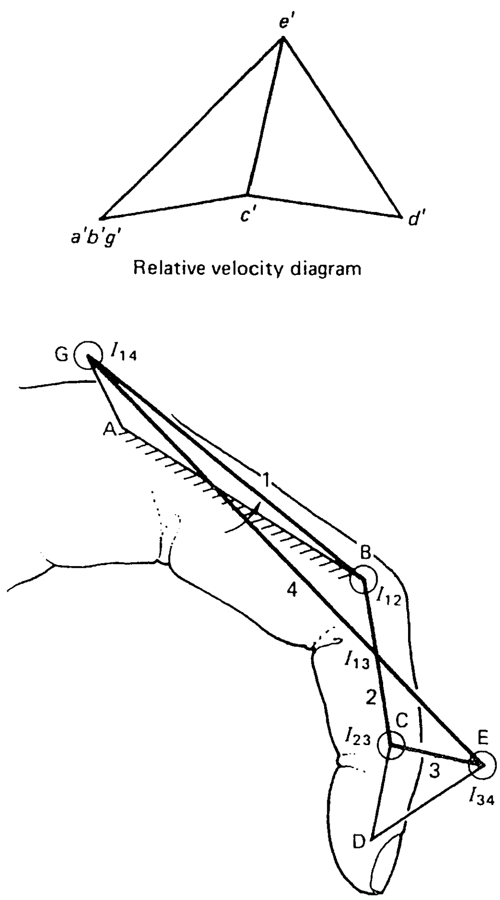
The ratio of the angular velocities is 1.9, a value which is very similar to the desired value of 1.8 so this design of orthosis would ensure that the normal physiological movement of the fingers is retained for the finger joint angles shown. This design however has not been adopted for general orthotic use because the required location of components between the fingers could irritate adjacent fingers and also because the desired synchronous motion of the orthosis is not retained when the instantaneous centre of rotation I_{13} is displaced during finger flexion and extension. This idealised kinematic behaviour is compared with the 'armchair' orthosis illustrated in figure 2.11.



$$\frac{\text{Angular velocity of distal phalanx}}{\text{Angular velocity of middle phalanx}} = \frac{160}{90} \simeq 1.8$$

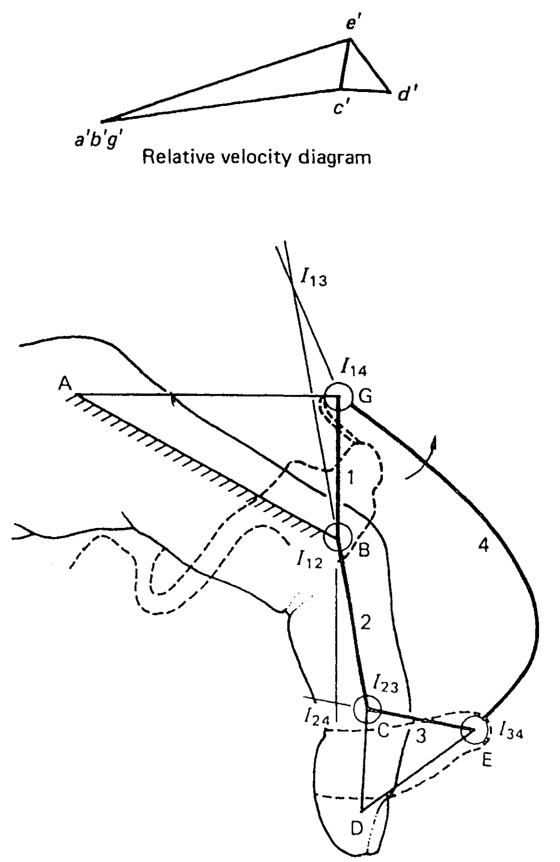
Synchronous motion of the distal and middle phalanges
with respect to the proximal phalanx

figure 2.9



Kinematic behaviour of an idealised
dynamic finger orthosis

figure 2.10



Kinematic behaviour of an 'armchair'
dynamic finger orthosis

figure 2.11

In this case, the angular velocity of the distal phalanx with respect the proximal phalanx is;

$$\frac{\text{velocity of E with respect to G}}{\text{distance between } I_{13} \text{ and E}} = \frac{g'e'}{I_{13}E} = \frac{73}{137} = 0.5$$

(from scale)

and the angular velocity of the middle phalanx with respect to the proximal phalanx is given by;

$$\frac{\text{velocity of C with respect to B}}{\text{distance between C and B}} = \frac{b'c'}{BC} = \frac{66}{48} = 1.4$$

(from scale)

The ratio of the angular velocities is 0.4, a value significantly different from the desired value of 1.8. The kinematic analysis does appear to be disappointing but the orthosis can be successfully used provided the dorsal link, GE, is able to increase in length during finger flexion to ensure synchronous interphalangeal joint motion is retained.

2.2.3 Description of current orthoses

Comprehensive descriptions of the methods for fabricating wrist hand orthoses have been provided by N Barr (1975), M H Malick (1978, 1979), M Ellis (1981); R M Duncan (1989); and J Rossi (1987). A summary of the essential considerations in the fabrication of wrist hand orthoses is provided below.

2.2.3.1 Materials - interface components

The principal material currently used for the construction of the interface components of wrist hand orthoses is thermoplastic sheet which can be moulded when it is heated to a temperature between 65^{o} and 80^{o} Celsius. The material can be applied directly to the body so a positive moulding cast is not usually necessary. This material does not possess either the strength or durability of high temperature thermoplastics although this is usually not critical for wrist hand orthoses which are required for relatively short periods of time. Orthosis construction using low temperature thermo-plastics requires only a simple heat source such as a hot water bath, trimming tools and suitable velcro fastening straps. Accordingly, orthoses can be quickly and relatively easily constructed from this material.

High temperature materials are also used for construction of wrist hand orthoses, especially those required for long term use. Furthermore, this material is used for the fabrication of interface modules used in some of the modular 'off-the-shelf' type orthoses systems now available. The principal advantages of using high temperature materials are that they are stronger, more rigid and durable than low temperature types. Their higher moulding temperature of 120^{o} - 180^{o} Celsius prevents the possibility of direct moulding to the patient. The moulding of these materials requires the production of a positive cast which consequently makes device fabrication both more complex and time consuming.

2.2.3.2 Materials - dynamic components

These are used to provide the required moments to the joints. The two main types of material which are used are rubber elastic and spring steel wire.

Elastic

Rubber bands or cords are widely used because they have the advantage of being readily available, cheap and easy to apply, adjust or replace. This material is not usually suitable either for long-term applications or when the patient requires to use his hand for functional or occupational tasks.

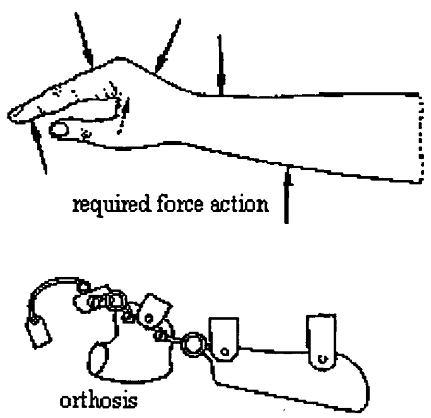
Spring Steel Wire

This material is also relatively cheap and widely available. It is usually used in the form of a coil with extensions for attachment to the interface components and finger loops. The centre of the coil is normally located on, or as near as possible to, the axis of rotation of the desired joint. The coil tension can be adjusted to create the required level of flexion resistance/extension assistance. With correctly sized and shaped extensions, springs can exert arcuate force vectors which offer the potential of forming a closer biomechanical match to normal anatomical joint motion than can be achieved with orthoses which use elastic bands. Spring wire is versatile than elastic bands since the coils can be adjusted to provide specific functional assistance or motion control. Such springs therefore, if correctly designed and applied, offer the potential of more effective control than elastic bands. Excessive levels of spring breakage may occur if poor quality wire is used or if the wires are incorrectly shaped.

2.2.4 Orthoses for the wrist

2.2.4.1 Radial nerve palsy

Damage or transection of the radial nerve severely affects normal wrist and hand function. The damage results in denervation of the wrist extensors and extrinsic finger extensors. It may be difficult or impossible for the patient to maintain normal active wrist extension, metacarpophalangeal joint extension, wrist abduction and adduction and normal finger pinch strength. The orthotic objectives are first, to support the wrist in an extended position and second, to support the metacarpophalangeal and interphalangeal joints in functional positions to aid recovery and prevent contractures. These are usually achieved with the use of a dynamic orthosis which features separate dorsal forearm and hand sections, connected together with spring wire coils located on both sides of the wrist joint. Corrective moments about the metacarpophalangeal joints are provided with the use of a transverse bar on the proximal phalanges, connected to the hand component with wire springs (figure 2.12). Moments about the interphalangeal joints are provided by wire springs attached at their proximal ends on the transverse dorsal bar, and at their distal ends with finger loops.



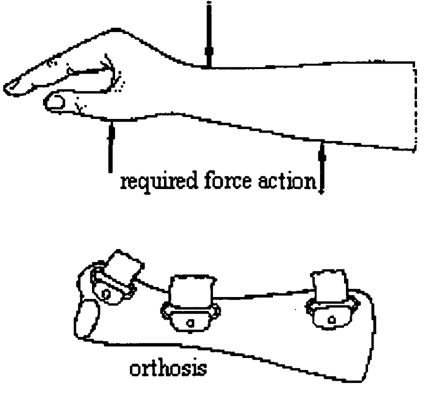
Dynamic orthosis for radial nerve palsy
figure 2.12

The effectiveness of this orthosis depends upon both the correct alignment of the individual orthotic components and the application of two interacting force systems. First, a wrist extension moment is achieved by the application of dorsally acting forces upon the volar surfaces of the forearm and palm, and a volar acting force on the dorsum of the distal forearm at the region of the ulnar styloid. A second dorsal forearm strap is often added proximally to improve retention, though this is not essential for the force system. The second force system creates a flexion moment at the metacarpophalangeal joint. This is achieved by the application of volar acting forces on the dorsum of the metacarpal and the first phalanx, the latter provided by the transverse bar. The opposing dorsal acting force is applied via the palmar section of the hand component. Extension moments about the interphalangeal joints are provided by a dorsal acting force on the distal phalanx.

2.2.4.2 Wrist extensor weakness

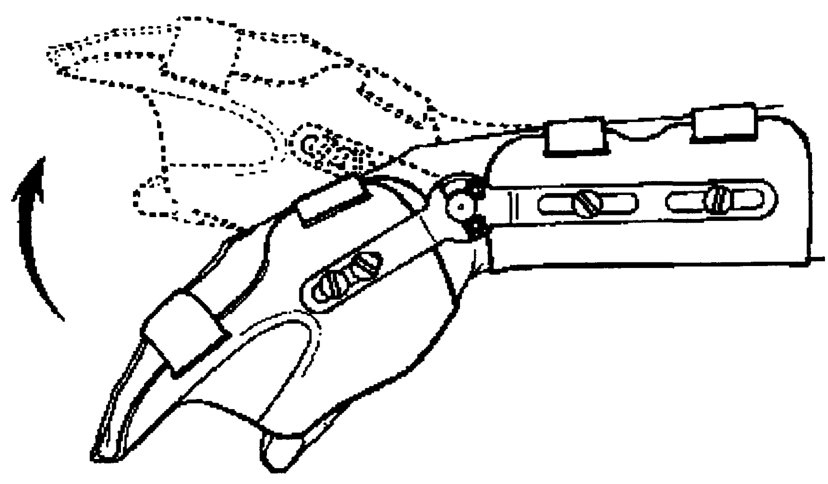
Wrist extensor weakness results in functional deficiencies, typically weak grasp and diminished control of the hand and fingers. In the presence of this weakness, the effect of gravity tends to cause wrist flexion when the elbow is flexed. Additionally, in clinical conditions such as hemiplegia when there may be severe spasticity in the unopposed wrist flexors, severe contractures may rapidly develop.

The orthotic objective is to hold the wrist in the neutral position pending recovery or, where recovery is not possible, to hold the wrist and hand in the best functional position attainable. The biomechanical requirements are met by the application of a three-point control system to stabilise the wrist joint (figure 2.13). The orthotic options include both static and dynamic orthoses, the choice depending upon the precise pathology being treated.



Static wrist orthosis for wrist extensor weakness
figure 2.13

A hinged version is illustrated on the next page (figure 2.14). Theoretically, only one dorsal counter strap is required but in practice additional straps are frequently added over the metacarpals and at the proximal end of the forearm section to improve attachment to the arm and improve retention. Dynamic devices most commonly feature a similar thermo-plastic construction but with separate hand and forearm sections. These are coupled



Hinged wrist orthosis for wrist extensor weakness
figure 2.14

together by means of coiled spring wire components located on the radial and ulnar sides. The coil tensions are adjusted to counterbalance the weight of hand. Using this type of device, it is possible to maintain hand position without eliminating residual motion, or the potential for the patient to exercise the wrist joint by flexing against the resistance of the springs.

2.2.4.3 The painful wrist

There are a number of conditions, which cause wrist pain. Osteoarthritis results in a reduction of joint space and bone sclerosis leading to the development of osteophytes. Tenosynovitis in the tendon sheaths at the wrist joint is characterised by swelling and discomfort. Keinbock's disease (avascular necrosis of the lunate) and non-union of fractured carpal bones causes persistent pain, as does a malunion of a colles fracture. Static orthoses which provide compression between the thenar muscles, the dorsum of the wrist joint and the distal end of the forearm, limit wrist movement and thereby alleviate pain. Static orthoses may also be prescribed prior to wrist arthrodesis surgery in order that the patient may experience the functional effects of wrist immobilisation.

2.2.4.4 Rheumatoid arthritis

Rheumatoid arthritis is a particularly destructive and disabling disease. It causes an ulnar drift deformity which affects all four fingers in 30% of female patients and 15% of male patients. The deformity is caused by synovitis, the proliferation of joint membranes and an increase in joint fluids. These stretch the radial collateral ligaments and the radial hood which stabilises the extensor tendons, leading to subluxation of the extensor tendons in the ulnar direction. Secondary contracture of the intrinsic ulnar muscles and the ulnar collateral ligament result in further ulnar drift. Ulnar drift may also be accompanied by radial deviation of the wrist which results in the typical 'zig-zag' deformity. Even now, one of the source references on patho-mechanics of ulnar drift is the one provided by Flatt (1971).

Orthoses may be prescribed before and after joint replacement surgery. Generally speaking, the preferred orthosis is a dynamic design which provides dorso-radially acting forces on the displaced phalanges. These devices provide gentle and continuous forces which strive to place and maintain the fingers in their normal position. Static orthoses also have a role for night time use and are useful in relieving morning joint stiffness. They incorporate dorsal straps which exert minimal pressure upon the joints to provide correction moments during sleep. 'Posts' fixed to the volar surfaces of the orthoses can be located between the fingers to provide radially acting corrective forces.

2.2.5 Orthoses for the fingers

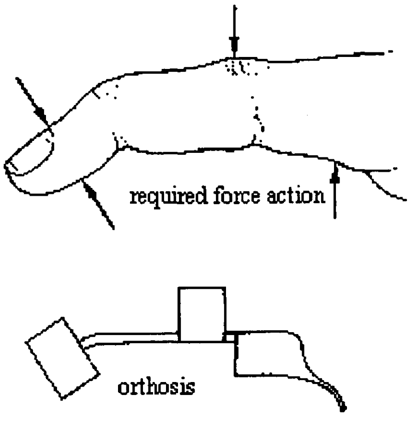
2.2.5.1 Flexor tendon repair

The management of zone II flexor tendon repairs remains one of the most severe rehabilitation challenges. The known risk of adhesions forming between the repaired tendon and its sheath is a strong clinical indication for early motion. Experimental studies (Matthews and Richards, 1976; Gelberman *et al*, 1980, 1982 and 1983) support the concept that the speed of healing and the strength of tendons can be improved by their mechanical environment. Hence, the purpose of an orthotic prescription is to provide relative gliding of the tendon with respect to its sheath. The most common orthosis design features a forearm section with an elastic band connected between it and the finger tip. The patient is encouraged to actively extend his finger against the action of the elastic band, which then returns the finger to its flexed position. This method was first described by Young and Harman (1960) and by Lister and Kleinert (Lister *et al,* 1977), described in section 1.2.2. A variety of modifications have been suggested and one of the most notable has been the use of a palmar pulley (Slattery and McGrouther, 1984) to improve flexion of the distal interphalangeal joint and hence the excursion of the profundus tendon. Lin *et al* (1989) studied the effects of different positioning of the elastic band and found that if it is placed in the usual position of providing a direct pull on the distal phalanx, the excursions of the flexor profundus and flexor superficialis in zone II were 10.1 and 7.8 mm respectively. When the orthosis was modified to provide a palmar bar under which the elastic band was passed, the excursions increased to 15 mm and 13 mm for the same tendons. Finally, if the palmar bar were retained and synergistic wrist motion was made, the corresponding tendon excursions were 19.8 and 15.2 mm respectively. In summary, the current design of an orthosis for flexor tendon repair, based upon biomechanical considerations, calls for a low profile volar elastic band, routed under a palmar bar, with synergistic wrist motion.

*2.2.5.2 **Boutonnière deformity***

This deformity is characterised by combined flexion of the proximal interphalangeal joint and hyperextension of the distal interphalangeal joint. It results from lengthening of both the middle slip of the extensor hood and the triangular retinacular ligament at the proximal interphalangeal joint. These cause palmar displacement of the lateral bands of the long extensor tendon and dorsal subluxation of the proximal phalanx. The deformity may arise either as a result of trauma, or dorsal synovitis which occurs in rheumatoid arthritis. Except for cases where the damage or deformity is slight, this condition, by its nature, is difficult to treat by the use of orthoses alone. Surgical repair is the primary method of treatment though orthoses are frequently used post-operatively.

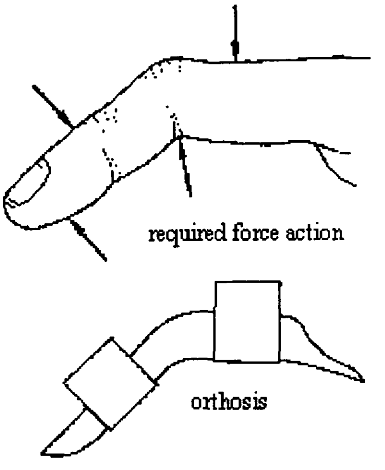
The orthotic objectives are to hold the proximal interphalangeal joint in extension and the distal interphalangeal joint in flexion, to reduce undesirable tension in the extensor hood whilst healing takes place. This may be achieved by the application of a four-point force system (figure 2.15). Dorsally acting forces are applied to the volar surface of the middle phalanx and at the proximal phalanx at the region adjacent to the metacarpophalangeal joint. Opposing volar counter-acting forces are applied over the dorsum of the middle phalanx adjacent to the proximal interphalangeal joint, and at the distal phalanx. Orthotic options include both static and dynamic orthoses. Static devices are most widely used, particularly for immediate post-operative management and for cases for which the damage or deformity is moderate to severe. The types of static devices include simple metal or thermoplastic volar gutters with straps over the distal phalanx and proximal interphalangeal joint regions. At a later stage in the recovery period, dynamic devices such as the Bunnell proximal inter-phalangeal joint extension/traction type of orthosis may be used. This consists of proximal and distal volar saddles, connected by two lengths of spring steel wire whose stiffness is sufficient to passively hold the proximal interphalangeal joint in extension, yet flexible enough to deflect during active flexion. The force system and arrangement of dorsal securing straps is the same as those for the static device.



Finger orthosis for Boutonnière deformity
figure 2.15

2.2.5.3 Swan neck deformity

This deformity is most commonly associated with rheumatoid arthritis but may also arise as a result of ulnar neuropathy, cerebral palsy, or Parkinson's disease. The appearance of the deformity is the reverse of the Boutonniere and is characterised by combined metacarpo-phalangeal joint flexion, proximal interphalangeal joint hyperextension and distal inter-phalangeal joint flexion. The condition is caused by subluxation of the lumbricals which leads to hyperextension of the PIP joint. This, in turn, causes tightness of the flexor digitorum profundus tendon with resulting distal interphalangeal joint flexion. The orthotic objectives are to reduce tension in the flexor digitorum profundus tendon by holding the proximal interphalangeal joint in flexion to arrest progress of deformity. Corrective action requires the application of a four-point force system (figure 2.16). A dorsally acting force is applied on the volar aspect of proximal interphalangeal joint and two opposing counter forces applied at the distal end of the middle phalanx. The proximal interphalangeal joint is held in a straight position by a volar force on the finger tip. Static orthoses are generally used for the management of this deformity and the most common is a flexed moulded thermoplastic volar gutter with dorsal velcro securing straps. Alternatively, a moulded thermoplastic cylinder retained on the finger by its shape and intimacy of fit may be used.

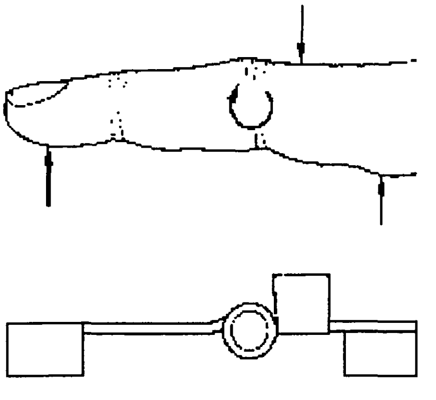


Finger orthosis for swan neck deformity
figure 2.16

2.2.5.4 Dupuytren's contracture

This deformity most commonly involves the ring and little fingers. It is caused by progressive contracture and thickening of the longitudinal bands in the palmar fascia and results in metacarpophalangeal and proximal interphalangeal joint contractures. Surgical release of the affected tissues offers the only effective treatment for this progressive condition and the role of orthoses is therefore in post-surgical management.

The orthotic objectives are either to prevent the development of contractures which may occur during the normal soft tissue healing period, or alternatively to reduce any residual contracture which may remain post-operatively. Biomechanically, the reduction of this deformity requires the application of a three-point force system configured to create extension moments at the affected joints.



Capener finger orthosis Dupuytrens contracture
figure 2.17

Several types of orthoses are available to correct flexion of the proximal interphalangeal joint. Two of the commoner types are the Capener (figure 2.17) and the 'armchair', though the latter can also be used for the metacarpophalangeal joint. The *Capener* (1967) type of orthosis features a spring wire chassis, whose side pieces are formed into a coil at the proximal interphalangeal joint. Volar saddles are located at the distal and proximal phalanges and a dorsal counter strap is located over the distal end of proximal phalanx to effect simple three-point control. When applied to a flexed finger, the coil creates an extension moment at the PIP joint. The advantage of this device over the 'armchair' orthosis (see below) is that it has no dorsal projections, is less obtrusive and therefore often more cosmetically acceptable. This design does however have some mechanical disadvantages. Its geometry and short lever arms become progressively less effective as the flexion angle increases. When used with a proximal interphalangeal flexion angle greater than 20^0, the functional effect of this design is significantly compromised due to the reduced distance between the opposing force vectors.

The *'armchair'* type of orthosis affects both the metacarpophalangeal and proximal interphalangeal joints. It consists of a malleable wire chassis with dorsal saddle located over the distal end of the proximal phalanx, a volar counter pad located on the palm proximal to the MCP joint, and a wire coil whose extension holds a finger loop which passes over the middle or distal phalanx. The spring tension exerts an extension moment on the proximal interphalangeal joint, the effect of which is to provide flexion resistance and extension assistance. Spring tension is adjusted in the same manner as described earlier. The advantage of the 'armchair' device over the Capener type is the fact that the dorsal counter forces are further apart and this reduces the magnitudes of each of the three forces. The disadvantage of this design is that the height, length and shape of the spring, required for functional effectiveness, unavoidably causes it to protrude over the dorsum of the finger, making it more obtrusive than the Capener type. Notwithstanding this, the improved mechanical effectiveness and reduced forces exerted by the armchair orthosis compared with the Capener design, currently render it the device of choice for the management of this condition.

2.2.6 Orthoses for the thumb

The thumb's importance for prehensile functional activities involving pinch and grasp cannot be over-emphasised. It is hardly surprising, therefore, that patients may be reluctant to use orthoses which limit thumb function. In general, the number of clinical conditions which necessitate the temporary use of a thumb orthosis is limited though the most important is the 'game-keeper's thumb'. This is a painful chronic metacarpophalangeal joint injury of the ulnar collateral ligament which can be treated conservatively with a static opponens orthosis. Pichora *et al* (1989) have reported good clinical results if the MCP joint is treated for six weeks in a removable custom-made orthosis with daily range of motion exercises. Static orthoses can also be applied for night use for patients with osteo- and rheumatoid arthritis. A small number of patients with motor neurone disorders, with poor ability to provide thumb opposition, may benefit from the use of opponens orthoses for specific activities but the majority of patients tend to reject them because they frequently interfere with sensation and function.

CHAPTER 3

OVERVIEW OF FINGER JOINT BIOMECHANICS AND PATHOMECHANICS WITH REFERENCE TO CONTINUOUS PASSIVE MOTION THERAPY

3.1 Introduction - Overview of finger joint biomechanics

Studies into finger biomechanics have been prompted by the desire to improve the design and effectiveness of joint replacements. These studies have concentrated on the forces transmitted across human finger joints, using predicted information about tendon moment arms and directions, the relative magnitudes of the intrinsic muscle tensions and the way that these forces are distributed within the finger. A number of models have been developed during the last two decades to analyse these variables for a range of finger configurations from pulp to tip pinch. Examples include those by Chao *et al* (1976), Seireg and Arvikar (1976), An *et al* (1979), Purves (1980), Purves and Berme (1980), and Weightman & Amis (1982). These models have been extensively used as a source of specification data for the development of joint replacements.

At the same time as the development of these biomechanical models, Professor Salter began his pioneering work on the biologic concept of **continuous passive motion, CPM,** on synovial joints. He had observed the deleterious effects of joint immobilisation and he tested the hypothesis that continuously and passively moving joints could stimulate pluripotential mesenchymal cells to differentiate into articular tissues.

He validated his hypothesis by numerous scientific investigations of a variety of experimental models of the knee joint. His biological tests were made upon full-thickness articular defects, intra-articular fractures, acute septic arthritis, partial thickness lacerations of the patellar tendon, semitendinous tenodesis to replace the medial collateral ligament, autogenic osteoperiosteal grafts in major defects, free autogenic periosteal grafts and periosteal allografts (Salter 1989). It became apparent that biomechanical models (such as those described above) had relatively little value for Salter in his pioneering work. Knowledge of tendon forces, intrinsic muscle tensions and joint forces did not have direct relevance in his biological research. However, the role of biomechanics in the study of treatment for tendon repairs (especially flexor tendons) is more obvious. Experimental studies, which provide data on the relative motion which occurs between tendons and their

Use of hand CPM

The current usage of hand CPM has been summarised in the following manner by Mr Rod Moore, Medical Dynamics, who has a commercial interest in the sale of these machines and has granted permission for his opinions to be published. In his view, the principal obstacle in the use of hand CPM machines is the physical difficulty of applying them to patients. Quite simply, they would be more widely used if they were easier to use. There are notable examples of individual hospital therapists devoting time to master the technical difficulties of preparing, applying and adjusting the machines but the majority tend to look on them as a 'tangled mess of metal'. However, he has frequently received frequent reports that they take long-term residence in cupboards unless enthusiastic therapists are available to use them. In addition to these practical difficulties, Mr Moore has described the prevailing financial considerations. Hand CPM machines are more widely used in the USA, Canada, Australia and Japan than in the UK because the former countries have established procedures for renting CPM machines for limited periods of say two or three weeks. Patients' employers, who want their employees to return to work as quickly as possible, frequently pay the rental costs especially in the USA. Unfortunately, funding structures in the UK tend to regard the purchase or rental of a hand CPM machine as an *additional* cost rather than a means of *reducing* the cost of hospital bed occupancy. A different outlook prevails in the USA where clinicians have more readily accepted not only the clinical benefits of hand CPM but also the financial.

Lin *et al* (1989) investigated the possibility of utilizing synergistic wrist motion in the application of hand splinting following flexor tendon repair. A comparison of the tendon excursions in three different postoperative treatment regimes was performed on cadaveric forearms under simulated passive and isotonic muscle tensions. Using the conventional dorsal splint with rubber band, the excursions of the flexor profundus and flexor superficialis in zone II were 10.1 and 7.8 mm respectively, so the relative motion between these two tendons was 2.3 mm. When the same splint was modified with an additional bar across the palm, the tendon excursions increased to 15 mm and 13 mm for the profundus and sublimis respectively. However, using the technique of employing synergistic wrist motion, the corresponding tendon excursions were 19.8 and 15.2 mm and relative tendon glide was 4.6 mm. Although the synergistic wrist motion technique increased flexor tendon excursions in zones II and III, excursion was less in zone V than with the other two orthoses, suggesting that synergistic wrist motion improves tendon excursion without increasing tension in the flexor muscles.

Notwithstanding the findings described above, the application of CPM to flexor tendon healing in zone II has been slow to evolve for two reasons; (i) concern that the tendon healing process might require ingrowth of connective tissue from the flexor tendon sheath so relative movement could be contra-indicated for tissue regeneration; (ii) concern about the mechanical integrity of the suture line. Gelberman *et al* (1982) have largely overcome the first concern by demonstrating that tendon healing could occur by an intrinsic mechanism of proliferation of epitenon and entotenon cells when an intrinsic mechanism was blocked by intermittent motion. They studied flexor tendon healing of the canine forepaw and found that not only did the tendon heal by the intrinsic route but the healing occurred more rapidly and with greater mechanical strength while simultaneously preserving the function of the tendon and the joints of the affected finger. Serious concern about the second issue remains, particularly if there is any possibility a CPM machine might behave in an uncontrolled manner because of a mechanical, electronic or software fault.

3.3 The biomechanics and pathomechanics of optimal joint positions following fractures

Fractures are the most common injuries presented at orthopaedic clinics. Inevitably, there is interest in the possible use of hand continuous passive motion to promote healing rate. This section considers the biomechanical factors which could influence the use of hand CPM.

3.3.1 Proximal and middle phalangeal fractures

The optimal clinical results following a proximal phalangeal fracture are obtained by methods that permit active interphalangeal joint motion and tendon gliding during fracture healing. The typical apex palmar angulation of proximal phalangeal fractures results in skeletal shortening on the dorsal side and a subsequent reduction in the effectiveness of the extensor mechanism with PIP joint extensor lag. Apex palmar deformities of the middle phalangeal fractures result in similar problems with skeletal shortening and a loss of distal joint extension. Functional restoration requires accurate skeletal realignment which restores normal skeletal length necessary for extensor tendon function. Agee (1992) advocated the use of an orthosis which holds the wrist in slight extension and the MCP joints for all four fingers in full flexion, combined with active interphalangeal joint exercises. Though not tested, continuous passive motion might be a useful adjunct to promote painless movement of the interphalangeal joints.

3.3.2 Comminuted distal radius fractures

The classic position of immobilization of a comminuted distal radius fracture is with the wrist flexed and in ulnar deviation. However, this is not the position of function and it often results in finger joint stiffness and a prolonged period of rehabilitation. Agee *et al* (1994) treated twenty consecutive, intra-articular fractures of this type using an external fixation system with the wrist in a neutral-to-extended position, thereby promoting metacarpophalangeal joint flexion by relatively relaxing the finger extensor tendons. Most patients were able to perform active digital motion on the day of surgery and 95% maintained functional finger motion during treatment. This method of fixing distal radial fractures allows restoration of anatomy while avoiding hand stiffness. This is an example of the application of an external device (in this case a fixator) to provide a particular joint position. It gives the prospect that the secondary addition of a CPM machine could also be beneficial to provide painless finger joint motion.

3.4 The biomechanics of CPM applied to wound repair

Van Royen *et al* (1986) compared the effects of immobilisation and continuous passive motion on surgical wound healing in mature rabbits. They performed parapatellar skin incisions and arthrotomies on both knees of ten mature rabbits. After closure of the incisions, one knee was immobilised in a cast while the other was treated by continuous passive motion for three weeks. Six standardised skin specimens (2 mm wide) from each wound were tested to failure and one specimen examined histologically. With respect to tensile strength, strain at failure and stiffness, the wounds in the CPM group were better than those in the cast group. Furthermore, histological examination showed that the structural organisation of the collagen fibres was also superior in the scars treated with CPM. The results indicated that compared to immobilisation, CPM enhances postoperative wound healing.

3.5 The biomechanics of CPM applied to connective tissue

The deleterious effects of stress deprivation occur rapidly and are profound, influencing joint mechanics, biochemistry and physiology in fundamental ways. The recovery from this process is not symmetrical, requiring many months rather than weeks to re-establish near normal values. In fact, mechanical strength of composite ligament structures does not regain normal strength even after twelve months of resumption of activity. Akeson *et al* (1987) have described the use of CPM to bypass some of the deleterious effects of stress deprivation and its application for the repair of cartilage, tendon, ligament and fractures. They have stated that benefits also include reduction in swelling and joint effusion, the possible reduction in the incidence of thrombophlebitis and shortened hospital stays. Finally, the clearance of blood from the joint space (by pumping action) is of undisputed advantage, knowing the harmful effects of chronic haemarthrosis in states such as haemophilia.

They conclude; *"Passive motion places in effect such fundamental cellular and tissue processes that we are probably observing only the infancy of its development."* Furthermore, *"The future directions of passive motion utilisation will almost certainly be expanded. Some of the potential applications discussed may be only the tip of an iceberg, due to the extremely fundamental nature of the cellular responses involved."*

3.6 Current usage of CPM

For centuries, clinicians have vacillated between the uses and benefits of rest versus motion in joint injuries. Orthopaedic opinion was strongly influenced by the knowledge that for tuberculosis, prolonged rest seemed to be beneficial so it was inevitable that joint treatment with motion would be controversial. The issues of indication, duration and value of passive joint motion are far from resolved.

Physicians have known for a long time that when the body is immobilised, overall physical fitness declines rapidly, the heart rate decreases, and muscles atrophy with a reduction of fibre size thereby resulting in the decline of tensile strength. The immobile body loses three percent of its original strength per day in a linear fashion for the first even days after which little strength is lost.

Motion is beneficial but continuous active motion is impossible because of muscle fatigue. It is now accepted that continuous passive motion is an important stimulus to joint regeneration processes and is clinically indicated following procedures such as open reduction of fractures, arthrolysis for post-traumatic arthritis, synovectomy, drainage of septic arthritis, release of joint contractures, total arthroplasty, tendon repair and ligament reconstruction.

Use of knee CPM

On these grounds, it might be assumed that CPM would be widely used. Indeed, most of the clinical experience with CPM has been in post-operative management after knee joint surgery. The majority of hospitals which offer joint reconstructive surgery and have accident and emergency (A&E) facilities have knee CPM systems, which are regarded as relatively easy to apply and convenient to use. It is generally accepted that the majority of patients who have had knee surgery obtain comfort with the equipment and remain in the machines for prolonged periods of time. One criterion for length of need is patient comfort when CPM is stopped. In the early phase of CPM, most patients prefer to keep the machine on because when it is stopped, the joint becomes painful slowly. When CPM is started again, there is a short period of adjustment while pain is reduced. This is apparently associated with the build-up of swelling. There are, however, two objections. The first criticism is whenever bed linen is changed or the patient moved, he or she inevitably moves out of alignment with the CPM system. The second criticism concerns the cost of commercial systems because they are regarded as being too expensive.

Use of hand CPM

The current usage of hand CPM is low and has not had the same impact as knee CPM. The situation has been summarised in the following manner by Mr Rod Moore, Medical Dynamics, who has a commercial interest in the sale of these machines and has granted permission for his opinions to be published. In his view, the principal obstacle in the use of hand CPM machines is the physical difficulty of applying them to patients. Quite simply, they would be more widely used if they were easier to use. There are notable examples of individual hospital therapists devoting time to master the technical difficulties of preparing, applying and adjusting the machines but the majority tend to look on them as a 'tangled mess of metal'. He has received frequent reports that hand CPM machines take long-term residence in cupboards unless enthusiastic therapists are willing to use them. In addition to these practical difficulties, Mr Moore has described the prevailing financial considerations. Hand CPM machines are more widely used in the USA, Canada, Australia and Japan than in the UK because the former countries have established procedures for renting CPM machines for limited periods of say two or three weeks. Patients' employers, who want their employees to return to work as quickly as possible, frequently pay the rental costs especially in the USA. Unfortunately, funding structures in the UK tend to regard the purchase or rental of a hand CPM machine as an *additional* cost rather than a means of *reducing* the cost of more expensive hospital bed occupancy. A different outlook prevails in the USA where clinicians have more readily accepted not only the clinical benefits of hand CPM but also the financial.

CHAPTER 4

REVIEW OF THE APPLICATION OF CONTINUOUS PASSIVE MOTION TO THE HAND

4.1 Introduction - The historical perspective and scientific basis for the use of continuous passive motion

4.1.1 Historical perspective

4.1.1.1 The advent of medico-mechanical therapy

Before the phrase, *'continuous passive motion'* was accepted into medical terminology, the development of externally powered therapy machines was largely attributable to the work of Zander (1835-1920) who invented numerous machines with the stated aims of *'strengthening muscles, promoting circulation, improving coordination, eliminating joint stiffness and easing the physical demands on the attending physician and therapy staff'*. He founded the first institute for medico-mechanical therapy in Stockholm in 1865 and his machines were publicly applauded by a group of prominent physicians of the time. His work spread from Scandinavia to Germany when Nebel took the Zander machines to Frankfurt-am-Main and promoted 'Zander Gymnastik'. Scholder (1861-1918) developed the 'Arthromotor', an outstanding machine which provided both active and passive exercise, permitted exact arcs of motion with regulated speed, and could be aligned with anatomical joints. His device was a milestone in the development of powered machines.

4.1.1.2 The demise of medico-mechanical therapy

Enthusiasm for medico-therapy subsided after the First World War for three reasons. First, the machines did not live up to expectations, for example they gave poor results for scoliosis. Second, new surgical methods became more aggressive and more successful. Finally, the Zander machines were expensive and bulky; for instance, a fully equipped Zander room required at least 300 square metres of floor space. Powerful critics emerged such as Haglund, one of the great orthopaedic surgeons of the early decades of the century, who wrote in 1923 that most of the Zander machines could be dispensed with and that manual gymnastics were superior. The physiotherapy profession grew soon after the First World War and by 1935, the demise of the Zander Institutes could not be halted.

Quengel therapy, which should use finely adjustable tensile or compressive forces to increase joint range of movement, achieved some notoriety because it was seen as crude and painful. For instance, it is reported that one in four patients report a decrease in range of movement, coupled with extreme pain, after passive manipulations of the elbow to release contractures. Even now, the application of externally powered machines conjures up images of horror frequently associated with the title 'Quengel Therapy'.

Some of the papers of the time published after the Second World War were quite vicious in their attacks upon 'soul-less machines' for use in rehabilitation. The philosophy of rest was advocated and by the 1950's, conventional medical practice required immobilisation in plaster for two weeks after arthroplastic surgery, followed by passive exercise in traction and active exercise four weeks after surgery.

4.1.2 The birth of continuous passive motion, *CPM*

It would have been a brave man to 'reinvent Zander machines' but interest in the application of externally powered machines resurfaced following studies into the effects of joint immobilisation and mobilisation, particularly those conducted by Salter *et al* (1979, 1980, 1981, 1984).

4.1.2.1 Effects of joint immobilisation

Eronen *et al* (1978), showed that immobilisation is associated with rapid decreases in glycoaminoglycan concentration in load bearing cartilage and that these metabolic changes are generally considered to be early events in the development of osteoarthrosis. Akeson *et al* (1980) demonstrated that fibrous connective tissue loses significant lubricating and buffering volume of water and glycoaminoglycan when immobilised. Critical interfibrillar distances decrease with a resulting increase in inter- and intra-molecular crosslinking of collagen, severe disordering of fibrous connective tissue and subsequent joint stiffness. Immobilisation may lead to venous stasis, thromboembolism and post-traumatic osteopenia in large joints. Immobilisation and stress shielding have significant adverse effects on the mechanical properties of tissue. Woo *et al* (1987) reported a forty six percent decrease in the elastic modulus of the stress-strain curve of the medial collateral ligament of the rabbit after immobilisation. Yamamoto *et al* (1989) showed that the elastic modulus of the rabbit patella tendon stress-strain curve decreased by ninety two percent and that strength decreased by seventy seven percent after stress shielding. In summary, it is now recognised that joint rest and immobilisation have detrimental effects for joint function.

4.1.2.2 Effects of joint mobilisation

Conversely, the biological benefits of joint mobilisation were demonstrated by the pioneering work of Salter, who investigated the effect of continuously and passively moving joints in a slow, repetitive and cyclic manner. He coined the phrase, *continuous passive motion*, and established a sound incontrovertible body of evidence to support the concept of its use. He reported, *inter alia*, that full thickness hyaline cartilage defects consolidate significantly faster and more completely under continuous passive motion treatment than under immobilisation or intermittent motion treatment (Salter 1980, 1984, 1989). Benefits were demonstrated on intra-articular fracture models, on acutely septic joints (Salter 1979, 1981) and on disorders and injuries of synovial joints (Salter *et al*, 1984). Other workers (Gelberman *et al*, 1982; O'Driscoll *et al*, 1983; Inoue *et al*, 1986) have provided strong supporting evidence of the benefits of CPM for the healing of flexor tendons, the clearance of haemarthroses and ligament repair.

Loitz *et al* (1989) demonstrated that even short-term immobilisation of three weeks caused significant differences between the biomechanical and biochemical properties of rabbit tendons subjected to CPM and immobilisation. Immobilised tendons were found to have twenty five percent less tensile strength than tendons subjected to CPM. Hydroxyproline concentrations, measured to determine tendon collagen content, were approximately six percent greater in CPM tendons than in control or immobilised tendons.

In an animal study of the effect of immobilisation upon joint stiffness, Namba *et al* (1991) showed that stiffness increased by a factor of 2.6 the pre-injury level, for limbs immobilised three weeks. Conversely, that was no statistically significant increase in joint stiffness in ankles treated with CPM compared to pre-injury values.

Gebhard *et al* (1993) compared the effects of passive motion versus immobilisation on joint stiffness, muscle mass, bone density and regional swelling after intra-articular injury to rabbits ankles. They determined that there is an inverse relationship between the duration of passive motion and the radiographic density of the distal tibial metaphysis, a relationship that was statistically significant.

The concept that the strength and excursion of healing flexor tendons can be modified by the mechanical environment has been supported by experimental studies (Matthews and Richards 1976, Gelberman *et al* 1982 Gelberman *et al* 1983). Furthermore, gradually increasing passive motion not only leads to significant increases in tendon tensile strength and excursion but also brings about a marked change towards normal peritendinous vessel density and configuration (Gelberman *et al* 1980).

4.1.3 Acceptance of *CPM* into clinical practice

The acronym *'CPM'* has been adopted into everyday medical language and CPM machines are widely available, especially for the knee. CPM use is considered established practice in the post-operative management of, *inter alia*, muscle and joint release surgical procedures (US Scientific Advisory Panels on General Surgery, Orthopaedics and Physical Medicine and Rehabilitation, 1984). Hamilton (1982) provided positive reports of his five years experience of CPM for severe intra-articular fractures of the knee, elbow and ankle, as well as other applications in which the objective was to promote chonroneogenesis and to avoid postoperative stiffness.

Patients have remarkably little pain when using CPM devices and this surprising fact is probably best explained by the 'pain gate' theory described by Melzack and Wall (1970). It is believed that CPM causes the proprioceptive receptors to provide considerable non-painful afferent input into the spinal cord ganglia. This input overwhelms the pain fibre input and thereby blocks the pain perception. It is also presumed that suitable CPM machines might provide pain relief in some hand conditions; Miehlke and Ehm (1982) reported that the loosening of periarticular tissue structures and the strengthening of finger muscles reduces pain.

The concept of applying external forces to finger joints, by means of powered CPM devices, is conceptually attractive but is not universally accepted. Indeed, the suggestion can evoke emotive comments concerning the pain, which *may* be associated with the passive stretching of tissues. In fact, these comments often originate with the teaching of the problems associated with the application of Quengel therapy (described in chapter four, section 4.1.1). Criticisms of Quengel therapy may be justified in a number of respects. Nevertheless, therapy by means of powered CPM is entirely different. The clinical advantages of CPM have been summarised by Blauth (1992) who states that swelling of periarticular tissue rapidly recedes and tissue repair is accelerated. CPM leads to decreased muscle atrophy and provides an essential contribution to the rapid recovery of joint function. Patients can move joints soon after injuries or operations, movements which they otherwise could not perform or could only perform with pain. The treatment is well accepted by patients who quickly become accustomed to the regularity and reliability of mechanical motions. In summary;

- CPM can be used at any time and treatment can be distributed for daytime and evening use to responsible patients following careful instruction from their therapists;
- personal constraints regarding set work hours can be overcome;
- CPM provides painless and well-regulated motion exercises, based on the possibility of completely relaxing the injured limb;
- the rate of movement and arc of motion can be exactly determined and easily changed;
- in the early post-operative management phase, CPM machines are superior to manually assisted exercise (which therapist wants to move a joint for hour after hour!) whilst traditional therapy can concentrate on improving coordination, restoring mobility, etc;
- patients rapidly adjust to the regularity, reliability and painlessness of mechanical motions. This relieves anxiety and promotes relaxation and an eagerness to exercise;
- the patient's self-esteem is enhanced. The pleasant regaining of joint function represents a very positive experience in the course of the treatment;
- CPM devices can be rented to patients for use at home, after an appropriate period of instruction from the therapist.

For the majority of patients, CPM provides;

- a more rapid elimination of motion limitations;
- painless or almost painless treatment;
- early post-operative success;
- therapeutic help that is available at all times of the day and night;
- the chance for a shortened duration of hospital stays and total rehabilitation time;
- support in carrying out an outpatient exercise programme at home.

For the physician and therapist, CPM provides;

- simple and reliable prevention of joint contractures;
- improvement of joint metabolism;
- improved resorption of joint effusion;
- prevention of muscle atrophy;
- rapid healing of injuries to soft tissue, bone, cartilage and ligament;
- prevention of thromboembolic disease and arthroses.

For the cost bearing institution, CPM provides;

- a possible reduction in medical costs.

4.1.4 Criticisms of *CPM*

Inevitably, there are criticisms of the use of continuous passive motion, which can be divided into two headings, namely those criticisms, which are based on scientific evidence which contradicts its use and those which reflect practical difficulties for the patient and the carers. They are discussed in turn below.

4.1.4.1 Contradictory scientific evidence

Creekmore *et al* (1985) undertook a study to compare the results of tendon function after a post-operative regimen of either early passive motion or immobilisation in all zones in two groups of 31 flexor repairs of 30 patients. They found no statistically significant differences between the two groups.

McCarthy *et al* (1986) evaluated the effects of CPM as an adjunct to tenolysis in a controlled study on chickens. They observed that CPM was associated with a significant increase in tendon rupture, a decrease in the passive range of motion and an increase in granulation tissue which formed around tenolysed tendon. Their conclusion was that passive motion does not appear worthwhile following tenolysis though it is worth observing that their control group was not immobilised but given immediate unrestricted motion.

Grauer *et al* (1987) showed that daily passive motion of the ankle for short periods of thirty minutes resulted in increased stiffness when compared with fully mobilised limbs. It appears that daily short periods of movement alternating with long periods of immobilisation actually promoted inflammation. Swelling increased probably because of inflammation produced by repetitive disturbance of granulation tissue. In that situation, motion represented repetitive trauma. Immobilisation is detrimental to joint function but short periods of motion may be worse if it cause inflammation.

Laupattarakasem (1988) found that although CPM applied to the elbow and knee provided a statistically significant improvement in range of movement, care had to be taken not to be too aggressive in the treatment. The most satisfactory regime was to start with only the range of movement which the patient could reasonably tolerate, then to increase the range progressively within the limits of discomfort. He commented that CPM may cause further tissue trauma and joints might have diminished movement after the cessation of CPM.

Gebhard *et al* (1993) in their study on rabbit ankles found that sixteen to twenty-four hours of passive motion each day for three weeks prevented stiffness of the joint. Shorter periods were ineffective, even harmful, and resulted in stiffness ratios that were as much as four times higher than those of the control limbs which were immobilised. Swelling of the limb decreased only in the group that received twenty four hours of passive motion.

In addition to these specific studies, sceptics say that CPM is a 'painful method of moving inflamed tissues'. Suspicions exist that the results obtained from controlled animal studies (which often involve immobilising rabbits and chickens by suspending them in slings) cannot be referred to clinical practice. Finally, there are difficulties in showing that passive motion *prevents* stiffness. Enhancement of cartilage repair, improvement in tendon gliding, clearance of haemarthroses, and improvement in the strength of bone, tendon, ligament and their attachments are all factors which may play a role in preventing increased joint stiffness but isolating one single factor is impractical.

4.1.4.2 Practical difficulties for the patient and carers

The significant difficulties for the patient and the carers, in the application of CPM, have been summarised by Blauth (1992) and are summarised below.

For the patient:

- Many patients enjoy the opportunity of attending a therapy department and the personal contact with a therapist. The machine might be regarded as a barrier to this contact.
- CPM treatment can be boring - many hours of use with the machine inhibit personal mobility.
- Machines must be applied with straps which may be uncomfortable and restrict blood circulation.

For the clinician and therapist:

- CPM might erroneously be regarded as a replacement for therapy.
  In fact, CPM should provide additional help to the therapy programme.
- Poor machine reliability leads to frustration and loss of confidence.
- The machines need to be regularly washed and disinfected.

For the purchaser: .

- Their cost effectiveness is difficult to quantify.
- The machines require space.
- Transport and storage can be problems.
- The machines must be serviced and maintained.

4.1.5 Critique of continuous passive motion with respect to the aims of the research programme

For centuries, there have been two schools of thought for the treatment of anatomical joints, typified by the 'rester' Hugh Owen Thomas and by the 'mover' Championnière. The 'resters' had dominated orthopaedic practice but Salter's work provided the scientific justification for moving joints for therapeutic reasons.

Salter had been obliged to concentrate his research on biological and animal studies and this was followed by related work by other investigators. The principal studies which resulted in positive statements for CPM were;

Eronen et al (1978)	cartilage glycoaminoglycan concentrations
Salter (1979)	intra-articular fractures
Akeson *et al* (1980)	loss of water and glycoaminoglycan in connective tissue
Gelberman *et al* (1980)	peritendinous vessel density and configuration
Salter (1980, 1984, 1989)	hyaline cartilage defects
Salter (1981)	septic joints
Gelberman *et al* (1982)	healing of flexor tendons
O'Driscoll *et al* (1983)	clearance of haemarthroses
Salter *et al* (1984)	disorders and injuries of synovial joints
Salter *et al* (1984)	disorders and injuries of synovial joints
Inoue *et al* (1986)	ligament repair
Gebhard *et al* (1993)	intra-articular injury (muscle mass, bone density and regional swelling); tibial metaphysis (radiographic density)

Biological and animal studies into the effects of continuous passive motion – positive findings
Table 4.1

Those which provided negative results were;

McCarthy *et al* (1986)	tenolysis in the chicken ankle

Biological and animal studies into the effects of continuous passive motion – negative findings
Table 4.2

Parallel biomechanical studies to the biological and animal ones concentrated on the effect of CPM on joint stiffness and the mechanical properties of tendon and ligaments. Those which resulted in positive results were;

Matthews & Richards (1976) Gelberman *et al* (1982) Gelberman *et al* (1983)	strength and excursion of healing flexor tendons
Woo *et al* (1987)	elastic modulus of the medial collateral ligament
Yamamoto *et al* (1989)	elastic modulus of the rabbit patella tendon; strength decrease after stress shielding
Loitz *et al* (1989)	biomechanical and biochemical properties of rabbit tendons
Namba *et al* (1991)	joint stiffness increased caused by immobilisation

Biomechanical studies into the effects of continuous passive motion – positive findings
Table 4.3

Those which resulted in negative or qualified results were;

Grauer *et al* (1987)	Joint stiffness (rabbit ankle)
Gebhard *et al* (1993)	Joint stiffness (rabbit ankle)

Biomechanical studies into the effects of continuous passive motion – negative findings
Table 4.4

The results of the wide-ranging biological studies, as well as the limited biomechanical studies, had been overwhelmingly positive. Admittedly, McCarthy *et al* had obtained a negative result though it is noteworthy that his animal study did not include an immobilised group. Grauer *et al* and Gebhard *et al* had not criticised CPM *per se* but had made qualified statements about the length of time CPM should be applied, claiming that it should be for long periods.

Discussions with orthopaedic colleagues at the Universities of Dundee and Berlin before the research programme commenced had confirmed the impression that biomechanical research into the role of hand CPM was justified. The medical efficacy of using CPM in clinical practice had been established but the clinicians observed that the majority of machines had been developed for large anatomical joints, such as the knee and hip. Relatively few were available for hand rehabilitation, even though the effects of hand disability can be significantly worse than those for the lower limb. They noted that published results of clinical trials for hand disorders were surprisingly sparse (they are reviewed in the next section) and that a great deal of work had still to be done to improve post-operative treatment techniques, especially following repairs for flexor tendon injuries.

Salter's work had made an enormous impact and a surge of CPM machines appeared on the commercial market. Many companies rushed to get patents lodged and products developed. However, a private discussion by the author with a leading manufacturer revealed that sales of his company's hand machines had been disappointing. His salesmen had reported that hospitals were reluctant to use hand machines which were regarded as potentially hazardous. Therapists were concerned that many CPM machines had powerful motors and that they were alarmed at the prospect of patients' fingers being forced into hyperextension. The reassurances which the salesmen gave had limited effect. There was also the problem that therapists receive very little technical training so they were discouraged by technical terminology in sales literature.

At the end of the discussion period, a collaborative research programme was proposed with the Universities of Dundee and Berlin. Internal examinations of joint spaces, as well as unnecessary surgical interventions were clearly not permissible and it was agreed that the research would be clinically based and would not involve laboratory dissections or animal studies. The programme would investigate the effect of CPM on finger joints with limited range of motion and would include the development of a prototype CPM machine for flexor tendon repairs. It was envisaged that two questions would have to be addressed, namely;

- Were there significant and unknown problems in applying hand CPM machines?
- Were the existing designs of machines appropriate, especially for the post-operative treatment of flexor tendon repairs?

Lengthy discussions about safety issues were held and it was agreed that although CPM treatment after flexor tendon repairs was a long-term goal, it would be unrealistic to attempt to apply an instrumented machine to patients with this condition because it was unlikely all safety issues could be satisfactorily addressed in the research period.

At the start of the research programme, Creekmore (1985) and Laupattarakasem (1988) had not completed their related studies. Comments about their findings are included in the discussion section of this thesis.

4.2 Clinical review of continuous passive motion applied to the hand

4.2.1 The requirements for hand CPM

Ever since Bunnell stated, *"Rigid splinting makes rigid hands"*, there has been emphasis on the benefits of lively non-powered orthoses which do not inhibit joint movement (Bunnell, 1946, 1950; Levame, 1965; Iselin, 1965; Capener, 1967; Wynn Parry, 1973; Ellis, 1981; Rossi, 1987; Burge, 1990). The development of hand CPM machines can be considered to be a natural development on the path of providing devices which retain and promote joint mobility.

The broad requirement for hand CPM is to prevent joint stiffness by providing gliding of tendons in their sheaths and movement of ligaments and other associated soft tissues, in order to prevent them from adhering to bones and surrounding soft tissue. Hand CPM could also be expected to prevent secondary effusions, increase joint range of motion in cases of joint stiffness, enhance metabolism of joint tissue and resorb effusions, provide mechanical stress on maturing collagen tissue, and reduce oedema. The clinical conditions are discussed in turn.

Limited finger joint range of motion (ROM), in particular active joint extension, is regrettably common after surgery, injury and disease. Limitation in joint extension is most commonly caused by flexion contractures and tightness of structures on the volar surface of the hand (Lister, 1984). These structures are the skin (for example scar tissue caused by burns), the palmar fascia (in Dupuytren's contracture), adhesions of the flexor tendons and their sheaths to bone proximal to the joint, and the capsular structures (the collateral ligament, accessory collateral ligament and the palmar plate). Osteosynthesis may be necessary to increase joint range of motion (ROM). The long list of surgical procedures which may result in flexion contractures are synovectomies, flexor and extensor tenolysis, aponeurectomies for Dupuytren's disease, metacarpophalangeal arthrolysis, open reduction and internal fixation of intra-articular, diaphyseal, metaphyseal and epiphyseal phalangeal fractures, capsulotomies, arththrolysis and tenolysis for post-traumatic stiffness of finger joints. Secondary conditions such as forearm fractures often lead to Sudeck contractures of the finger joints (Mucha, 1980).

Immobilization typically results in a reduction in interstitial fluid between the individual collagen fibres or fibrils, reductions in glycosaminoglycan content which alters the pliability of connective tissue matrices and lubrication efficiency, and anomalous crosslinking of collagen with subsequent reduction in independent fibre mobility (Akeson *et al*, 1980). These changes can be expected to occur after bruises, burns, infections, multiple traumas to the tendons, as well as joint inflammation attributable to polyarthritis.

Swanson has reported the need to apply stress to fibrous tissue as it matures and encapsulates a silicone joint replacement after arthroplasty. This is currently achieved by fitting a bulky dynamic hand orthosis, which is worn for approximately six weeks. If the patient does not wear the orthosis, the functional outcome may be poor. There is clearly a potential role for a CPM machine for enfeebled or poorly motivated patients who have undergone prosthetic replacement of the finger joints.

It is generally agreed that hand CPM is indicated for a remarkably wide variety of conditions but contra-indicated in cases of acute and chronic inflammation, unstable fractures and septic tenosynovitis, joint flexion contractures caused by capsular tears or distortion of articular surface congruence, osteophytes, synovitis of a flexor tendon ('trigger finger'), and loose bodies. Also unsuitable for manipulation by CPM are congenital conditions such as camptodactyly, symphalangism, arthrogryposis etc. There is some disagreement concerning its use in cases of post-operative cerebral paresis. For instance, Blauth (1992) reports that spasticity can increase during exercise endangering surgical results, though Haimovici (c.1980) has used CPM for five post-operative cerebral paresis patients. It is probable that no hard rules can yet be formulated for neurogenous conditions.

4.2.2 The application of hand CPM for particular clinical conditions

CPM for the hand has not had the same impact as CPM for the lower limb. Indeed, a review of papers on the use of *CPM*, published in the clinical literature since 1980, revealed that seventy five per cent of papers refer to *CPM* applications for the knee joint. This reflects the facts that a large number of arthroplasties are performed upon the knee and the joint is relatively large and easy to apply a machine to - conditions which do not exist for the hand. A summary of the limited number of clinical papers describing the results of applying CPM to the hand is provided below.

4.2.2.1 CPM for joint stiffness

The onset of joint stiffness may be sudden and rapid. McLardy-Smith *et al* (1986) reported severe intrinsic muscle contractures after forty-eight hours of immobilisation, though this might be considered an extreme case. A report on a controlled study of the effect of CPM on stiff joints has been provided by Ketchum *et al* (1979) who used an electrically driven hand splint to passively exercise fingers. Four hundred and twenty-six joints in one hundred and forty two fingers were studied to compare the stiff fingers exercised over a one month period with similar stiff fingers treated by conventional exercise. There was a statistically significant improvement in the mean gain of both total active and passive motion in those fingers treated with the electrically driven splint.

4.2.2.2 CPM for the reduction of oedema

Oedema frequently persists beyond the normal healing time for patients with paretic upper extremities and for patients with post-surgical or post-traumatic oedema and prevailing treatment results are often not satisfactory. Petrone and Calvanio (1989) reported the promising use of CPM to control upper extremity oedema in the hemiplegic patient. The topic was subsequently researched by Giudice (1990) who provided statistically valid data to support the assumption, that since both limb elevation and passive motion could independently enhance venous and lymphatic drainage from the hand, the most effective treatment for reducing hand oedema is CPM combined with limb elevation. Her study supported the hypothesis that thirty minutes of CPM of the digits, in combination with limb elevation, results in a significantly greater reduction of hand oedema than thirty minutes of hand elevation alone. The modality would appear to be especially indicated for patients who do not respond to traditional treatments for oedema reduction, due to impaired ability to move or use the hand.

4.2.2.3 CPM after flexor tendon repair

The treatment of flexor tendon injuries in zone II of the hand presents considerable difficulties (Strickland, 1989). It is inevitable that consideration should be given to evaluate the potential value of continuous passive motion for this major rehabilitation challenge, as an adjunct to supervised therapy. It is known that mobilisation after flexor tendon repair lessens the likelihood of adhesions and joint stiffness. Active mobilisation, however, is not widely adopted because of the fear of rupture at the repair site, though Cullen *et al* (1989) have reported its use under carefully controlled conditions. Treatment with the use of the Kleinert splint is popular but because flexion of the MCP joint produces little differential tendon movement, the original Kleinert splint is sometimes modified to introduce a palmar bar to encourage movement of the IP joints. It is noted that Chow *et al* (1987) and Werntz *et al* (1989) have stressed the importance of mobilising the DIP joint in order to gain maximum excursion of the tendons. The use of a Kleinert splint (or one of its modified forms) depends upon the cooperation of the patient as well as considerable time from the therapist. CPM offers the potential advantage of circumventing poor patient motivation and providing continuous twenty four hour treatment.

Bunker *et al* (1989) have reported upon the use of the first generation Toronto Mobilimb (Saringer 1987, Saringer and Galbreath 1991) for 20 patients with 35 flexor tendon injuries. Patients were encouraged to use the machine continuously for four and a half weeks from the time of repair. Excellent or good results were obtained in 85% of cases. Three problems were reported; first, it proved necessary to provide maximum flexion of the MCP joint by adjustment of the splint, in order to obtain full extension of the PIP joint; second, the elastoplast used to attach the actuator rod to the finger tip required to be frequently changed; third, the CPM machine gives very little movement in the DIP joint.

Gelberman *et al* (1991) undertook a prospective study to compare continuous passive motion with a modified Duran protocol for patients with acute flexor tendon injuries.

Patients who received CPM obtained significantly increased digital motion and the authors believed that an increase in duration of rehabilitation and the number of cycles was responsible for the improved results with CPM.

4.2.2.4 CPM after burn injury

Covey *et al* (1988) undertook a prospective randomised study of ten patients with bilateral (deep second degree and/or third degree) hand burns requiring excision and grafting in order to evaluate the efficiency of CPM with burned hands to identify (i) which patient populations benefit from CPM intervention, (ii) whether CPM use has deleterious effects on new grafts and (iii) what effect CPM has on hand pain. They found that eight hands in the control group and eight hands in the experimental group regained normal total active motion (TAM) in an average of nine days (range three to twenty two days). Both groups reported only minimal pain during exercise. However, the control and experimental groups seemed to be too small to make definitive comparisons.

4.2.2.5 CPM for polyarthritis

Haimovici (c.1980) has reported upon the use of the Manumobil A5000 device (Pasbrig, 1982, 1983, 1991) on 151 patients, of whom 78 were described as 'polyarthritic' (the other cases were 42 post-traumatic, 9 Dupuytren's disease, 8 Sudeck, 14 miscellaneous). He obtained favourable results and stressed the need to carefully adapt the machine to suit the individual characteristics of every hand. He found that the movements in both planes (i.e. flexion/extension, abduction/adduction) must be adjusted in steps. The period of treatment can be expected to be protracted and an average time of four and a half months was stated. On average, the machine provided 60-65 degrees of ROM for the PIP joints, and the respective figures for the MCP and DIP were 50 and 25 degrees.

4.2.2.6 CPM for general rehabilitation

Morris (1987) has reported his favourably prospective study of the use of the Toronto Mobilimb on twenty postoperative cases of flexor tenolysis, extensor tenolysis with or without extrinsic release, intra-articular fractures, flexor tendon repair, arthroplasties, dystrophy, Dupuytren's contracture and proximal interphalangeal joint contracture.

4.3 Technical review of hand continuous passive motion machines

The small sizes of the phalanges and the thirty degrees of freedom in the normal wrist and hand place considerable obstacles in the design and application of hand CPM machines. It is extraordinarily difficult to design a machine, which provides controlled passive movement of *all three* joints for *all* the fingers. Ingenious machines have been described but no single design has emerged as a front-runner. Existing designs can be grouped into three broad categories, namely those which

(i) provide their function by providing arcuate movement;

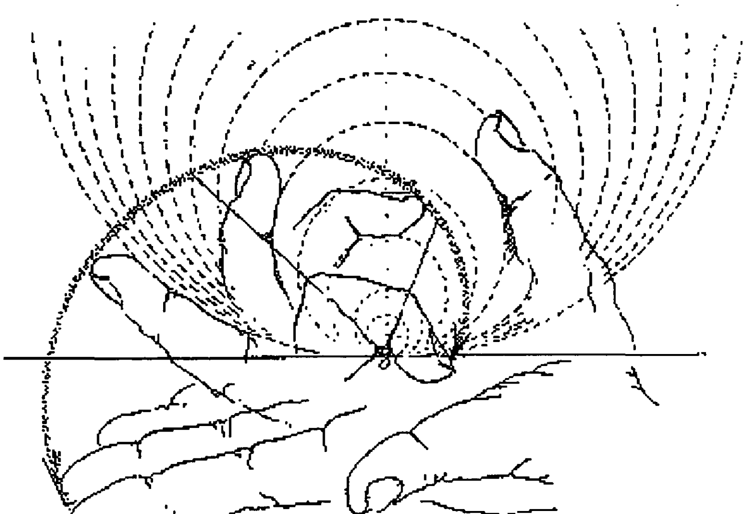
(ii) provide linear reciprocating movement;

(iii) use an expanding flexible container in the palm of the hand.

Devices in each of these three categories are described below.

4.3.1 Arcuate motion devices

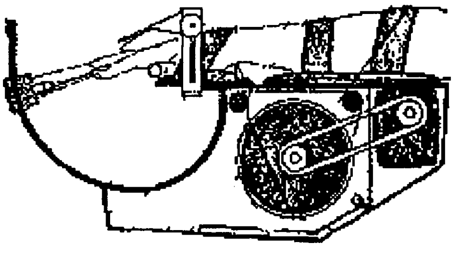
It is not surprising that a number of machines have attempted to provide either a single arc of movement for a finger joint, or alternatively mimic the natural spiral motion of the fingers described by Littler (1973).



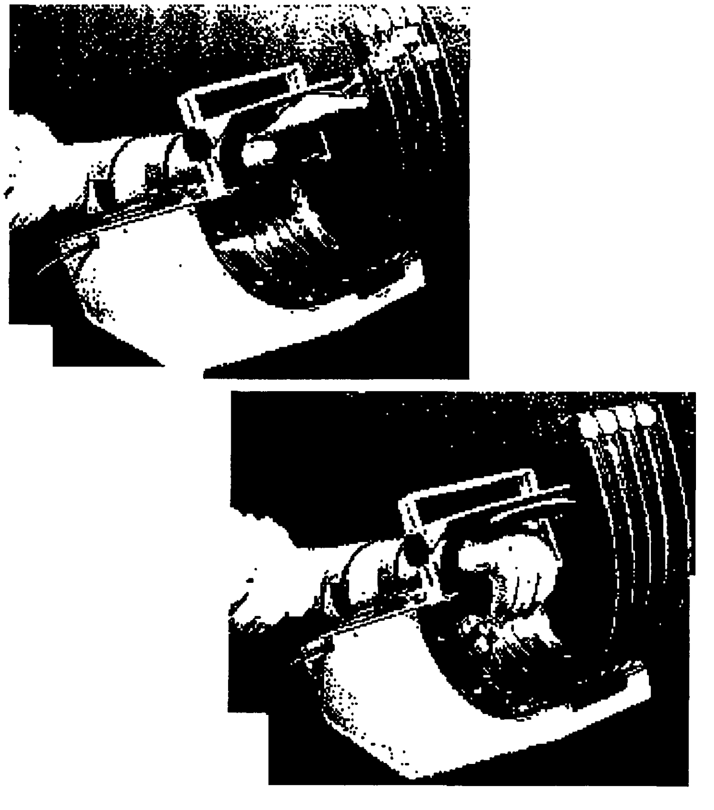
Spiral motion of a normal finger – Littler, 1973
figure 4.1

However, it is apparent that the task of designing suitable mechanisms is extraordinarily difficult because fingers do not share the same planes of motion, they are small and have different lengths, and the lengths of the palmar surfaces of the proximal and middle phalanges are shortened in full flexion, restricting the physical application of orthotic components.

The original machine described by Ketchum *et al* (1972) was intended to passively move repaired tendons during the seven or eight hours of sleep each day. It was rather bulky and obtrusive but the design was later significantly improved (Ketchum *et al*, 1979) when the principal use of the machine was to mobilise stiff joints during day-time therapy. Features were introduced to make it more compact and durable and to provide a means of individually adjusting the range of movement of each finger (figures 4.2 and 4.3).



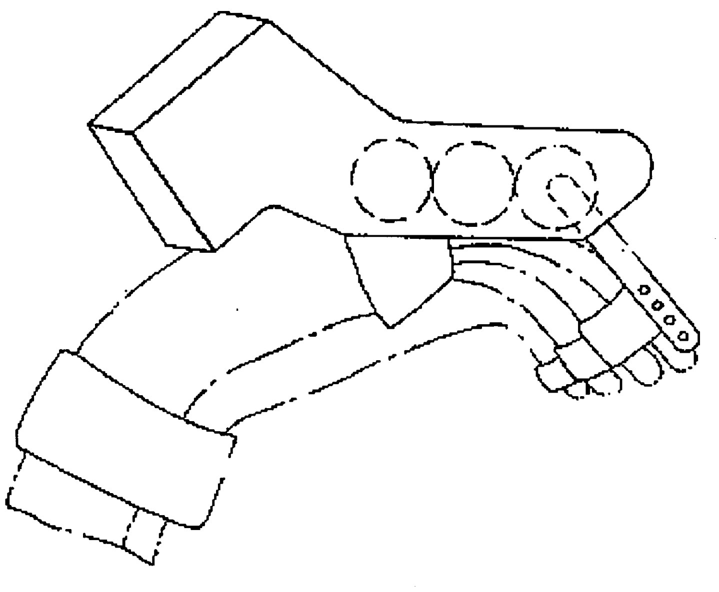
Hand CPM machine – Ketchum, 1979
figure 4.2



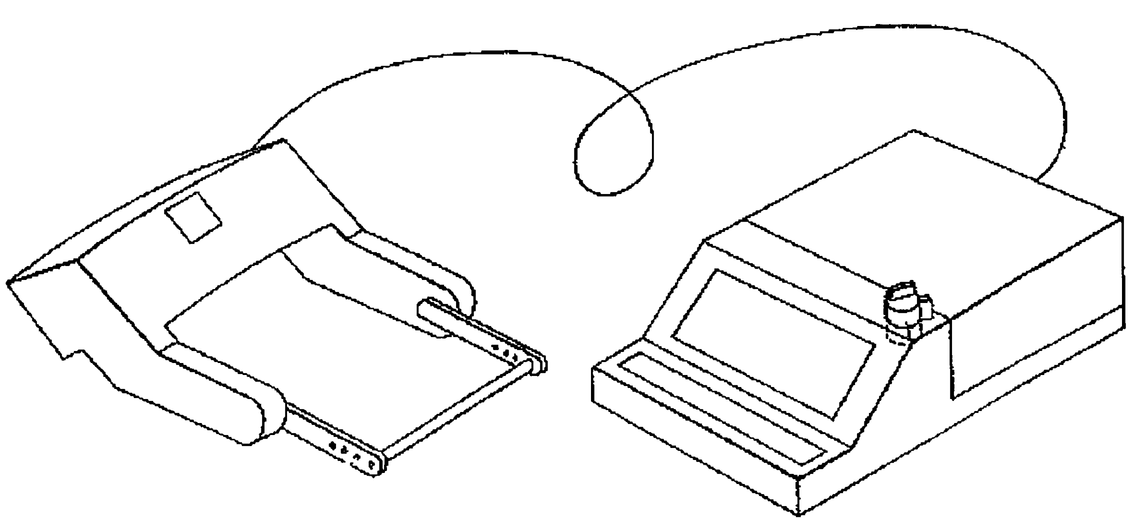
Range of motion for CPM machine, Ketchum 1979
figure 4.3

Significantly, the designers stated the need to be able to apply the machine with the hand in an elevated position.

The Sutter machine, designed by Koerner *et al* (1985), has a drive unit located on the dorsum of the hand, from which two arms extend down the radial side of the index finger and the ulnar side of the little finger (figure 4.4). Each arm includes a gear train to which moveable drive arms are connected at one of two points for rotating the selected joints. The gear train in each arm conveys rotational movement to the fingers. The axes of rotation of the links are set up as close as possible to the axes of rotation of the joints. The machine can provide a range of movement from zero degrees of extension to 135 degrees of flexion. Its features include programmable range and rate of motion, time to run, elapsed time, and maximum magnitude of force exerted by the finger drive rod. It is driven by a stepper motor (figure 4.5).

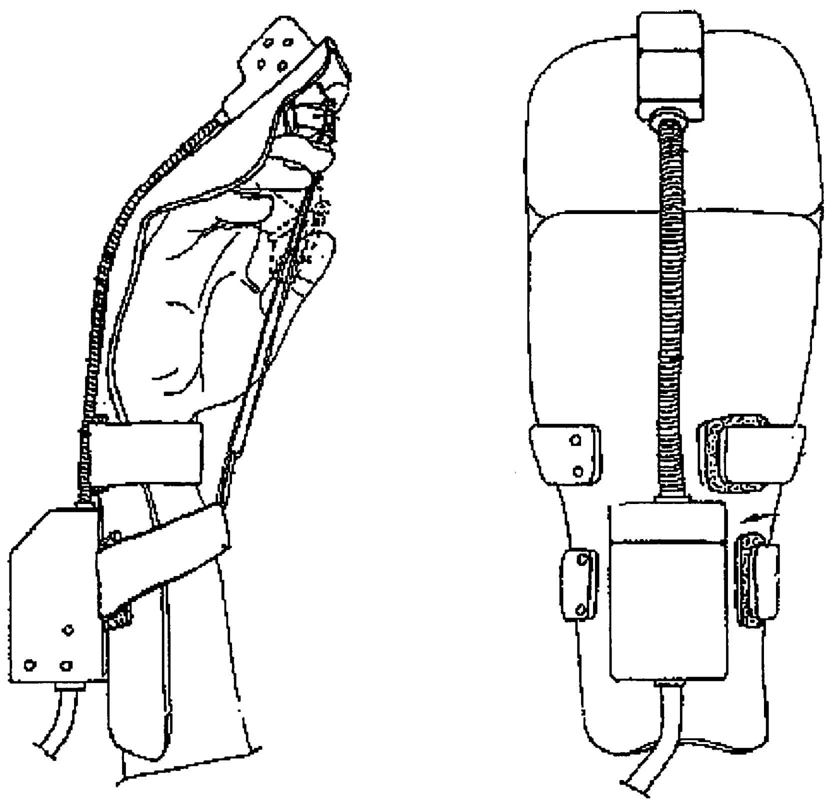


Hand CPM machine (Koerner et al, 1985)
figure 4.4



Hand CPM machine (Koerner et al, 1985)
figure 4.5

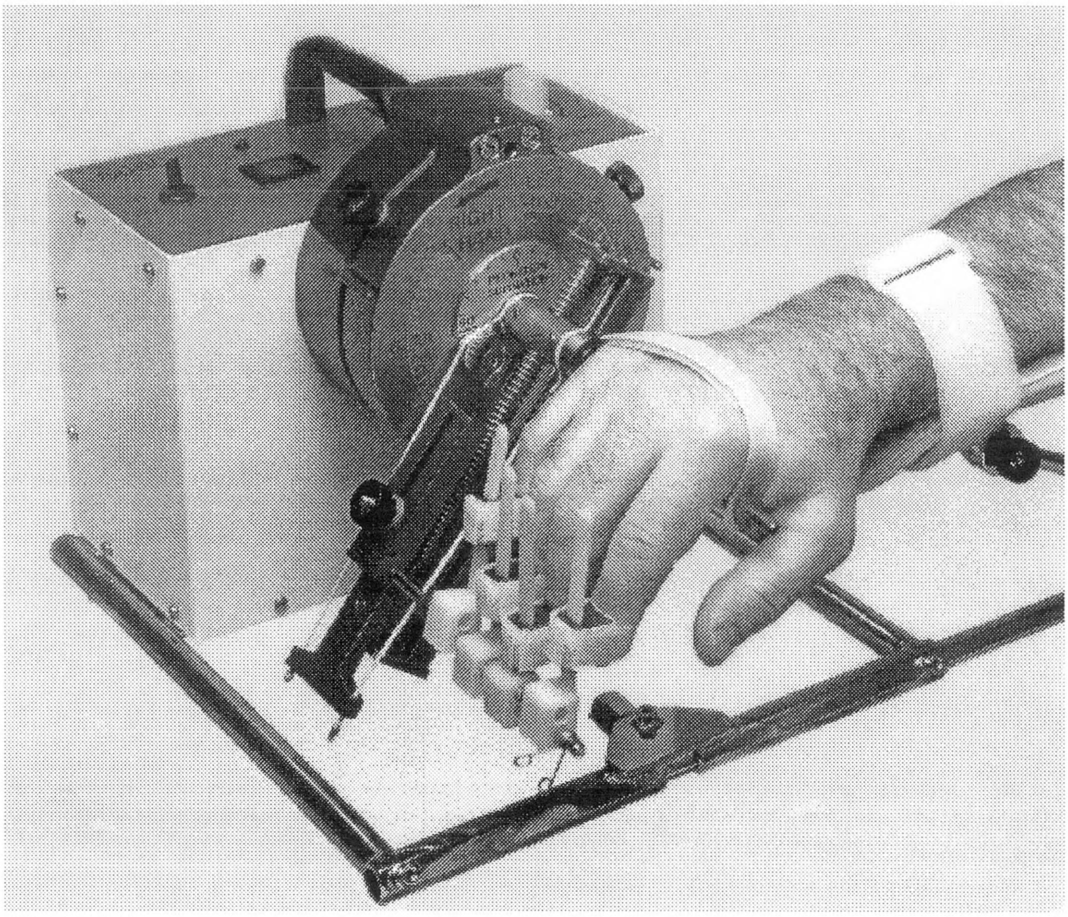
Yates *et al* (1987) have described a machine which uses a splint shell, moulded to fit the backs of the fingers and connected to the fingers by straps (figure 4.6).



Hand CPM machine for flexor tendon injuries, Yates et al 1987
figure 4.6

An elastomer, which is situated between the distal tip of the finger and an attachment point on the wrist, attempts to continually draw the finger into flexion. A reversible motor mounted on the dorsum of the hand and distal forearm applies tension to a cable which is wrapped around a feed drum in the machine and is attached to the distal end of the shell. This pulls the shell (and hence the fingers) into an extended position. The mechanical drive mechanism includes provision for sudden involuntary finger motion, which might occur during sleep, and this also provides for active extension. Thumb-wheel switches set the limits of motion.

The Kinetec hand and wrist 8080 machine (figure 4.7) has a flexible cable which passes over a cam to cause a slide block to be progressively drawn to the motor axis. The block is attached to the finger tip which is moved in a physiological arc. Soeters *et al* (1990) have stated that this movement is not always needed, for instance after an MCP joint

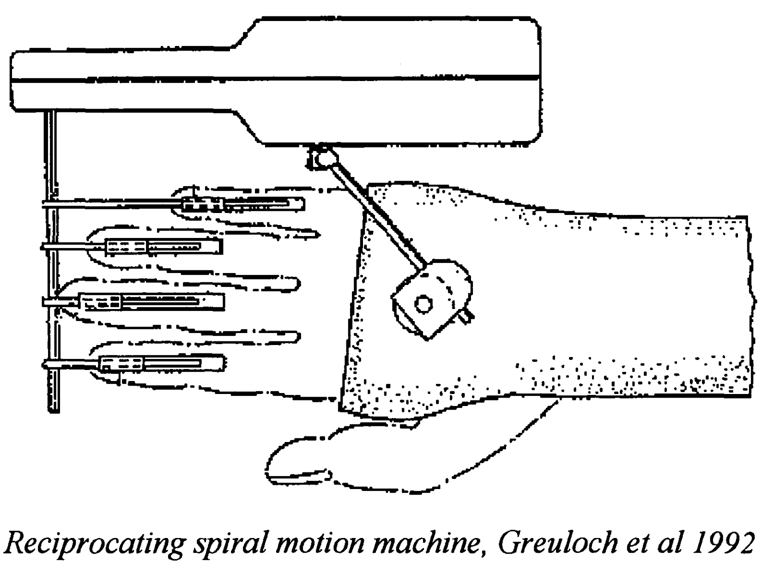


Kinetec hand and wrist 8080 CPM machine
figure 4.7

capsulotomy when it is more desirable to provide a constant radius of movement about the MCP joint without simultaneous movement of the PIP joint. They have proposed a modification to replace the cam with a plate with moveable pins, thereby altering the point at which the variable arc begins.

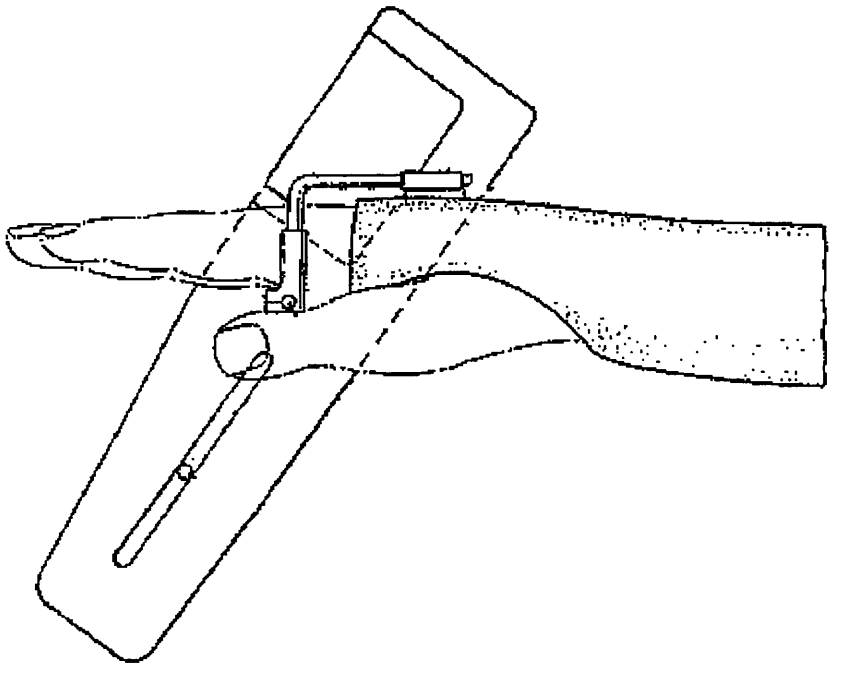
At a seminar discussion held at the 11th World Congress of Occupational Therapists (London, 17-22 April 1994) a poll was taken of the delegates to ascertain the preferred type of hand CPM machine. Approximately one half of the therapists present reported that they had used the Kinetec hand and wrist 8080 machine at some stage and it seemed that this machine was the most popular at that time.

A portable battery driven machine which provides a reciprocating spiral motion to the fingers has been described by Greuloch *et al* (1992), to cause a spiral motion of the fingers to achieve complete flexion and extension of the each digit (figures 4.8 and 4.9). The spiral motion is provided at a point near the distal end of a digit. It has a two-part linkage to provide a varying axis of rotation. The device is located on the ulnar aspect of the hand and forearm and is mounted on a splint fixed to the dorsal side of the hand. It is driven by a single motor energised by two small batteries. Telescopic finger mounts include spring-loaded members biased outwardly by a spring. A solid state relay circuit which is fed information from a potentiometer controls movement. When the desired limit of flexion is



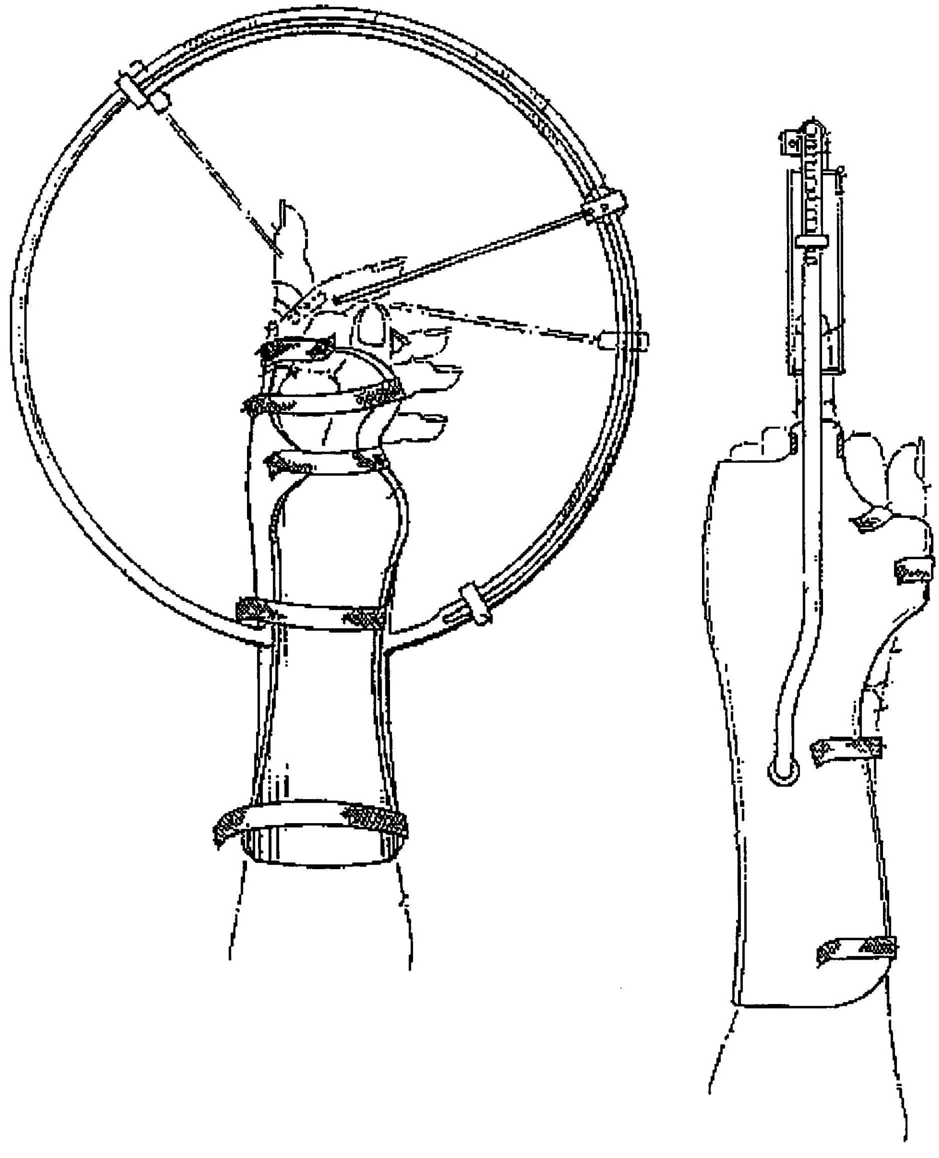
Reciprocating spiral motion machine, Greuloch et al 1992
figure 4.8

reached, the relay reverses the direction of the motor and consequently the direction of the rotation. Like the Toronto Mobilimb machines, it has been designed to be lightweight and highly portable. It can also be used for the thumb.



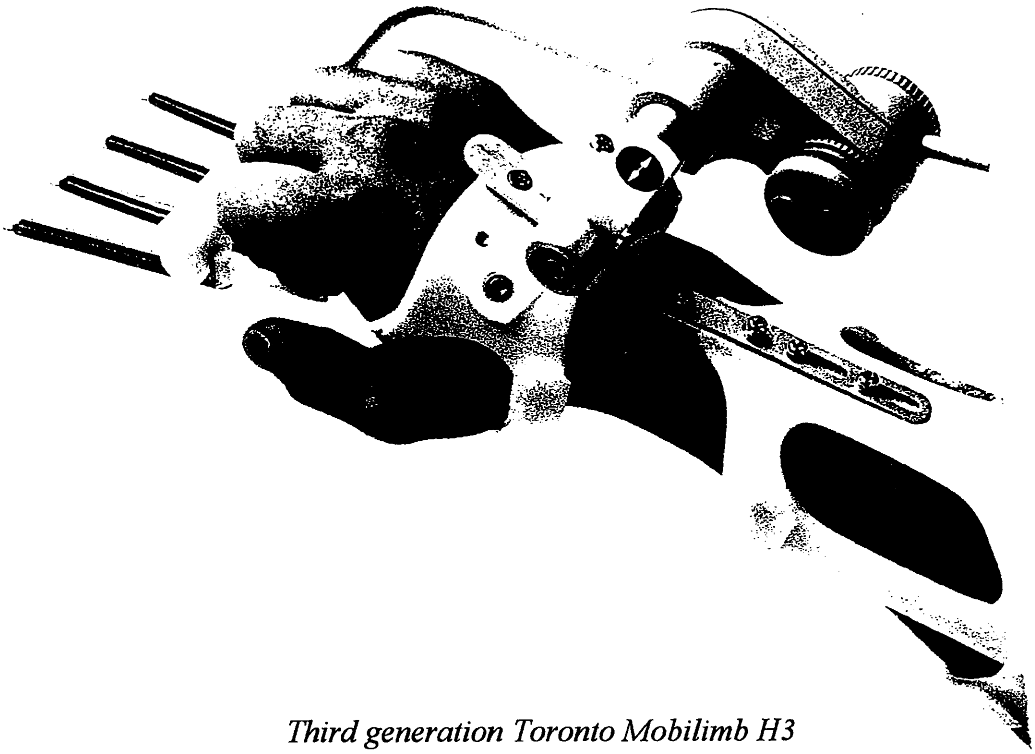
Reciprocating spiral motion machine, Greuloch et al 1992
figure 4.9

Schenck (1986, 1986, 1988) has described an ingenious hand CPM machine for the treatment of phalangeal bones with comminuted fractures (figure 4.10). It is well known that the consequence of a bone fracture is stiffness and deterioration of cartilage tissue in the joints to which the fractured bone is connected, particularly the joint immediately proximal to the fractured bone. The portable machine uniquely provides both traction and continuous rotary motion to fingers. The device uses a splint, typically made by therapy staff, which immobilises the joints proximal to the joint nearest the fracture. A ring around the finger and an elastomeric element connects a Kirschner wire, inserted through a hole drilled in the phalanx, to a small motorised element which slowly moves around a cogwheel on the loop. Limit stops are incorporated for safety.



Hand CPM machine for comminuted fractures, Schenck 1986, 1986, 1988
figure 4.10

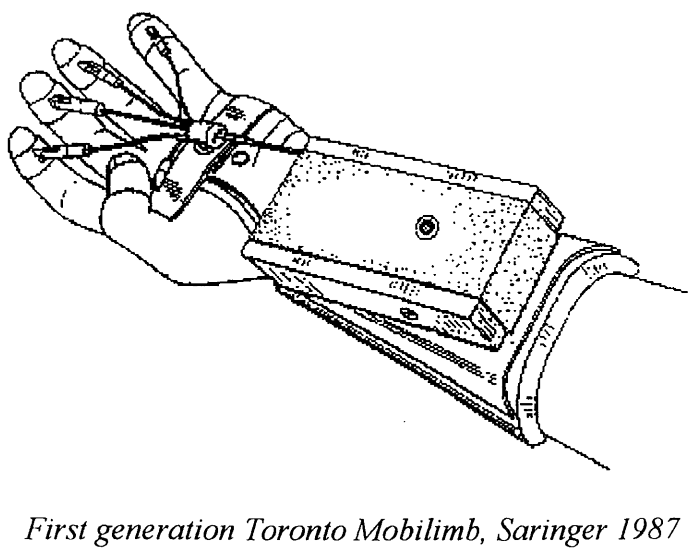
The third generation Toronto Mobilimb H3 (figure 4.11) provides arcuate movement, unlike its two predecessors which both provided linear movement. The H3 machine can provide joint movement from extension to full composite flexion then to the intrinsic plus position, or alternatively from extension to the intrinsic minus then intrinsic plus positions.



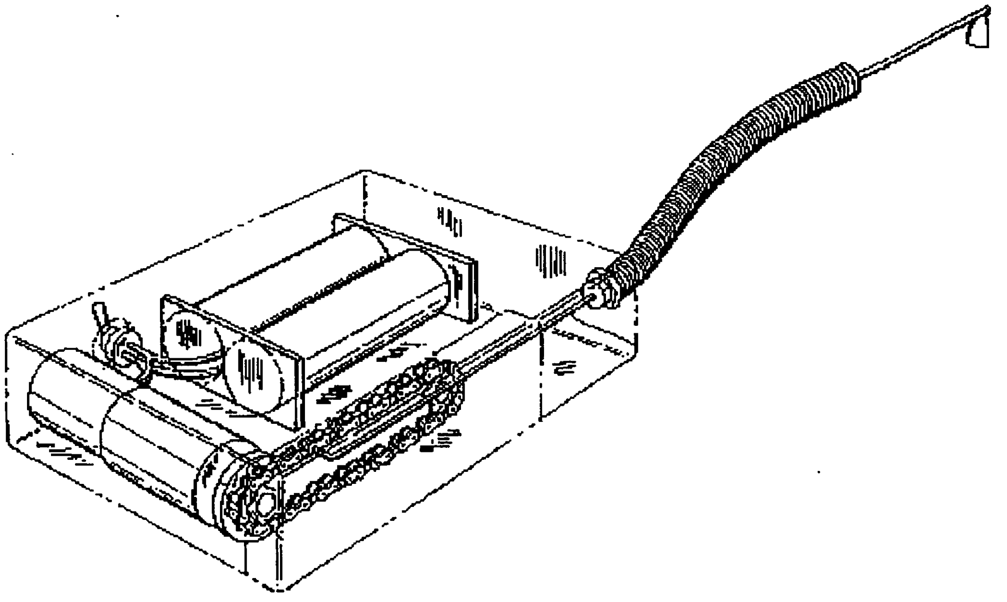
Third generation Toronto Mobilimb H3
figure 4.11

4.3.2 Linear reciprocating movement devices

The most well known hand CPM machines in this category is the first generation Toronto Mobilimb (figures 4.11 and 4.12). This was the fore-runner of modern commercial hand CPM machines and many were sold chiefly when CPM became a popular form of treatment. It was simple to apply but suffered the considerable disadvantage that it could openly pull finger joint sinto flexion, whereas the predominant need is to push them into extension.

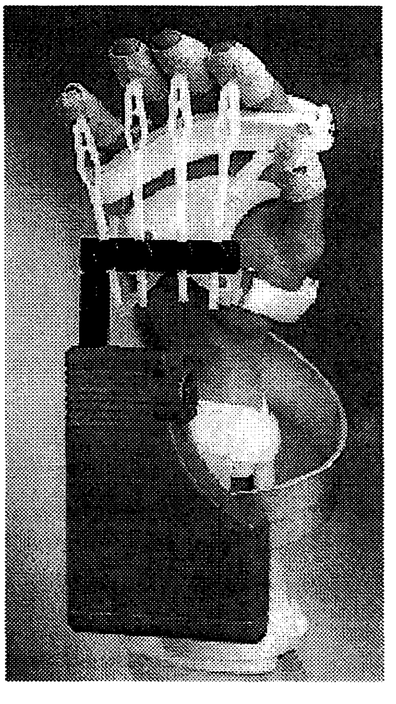


First generation Toronto Mobilimb, Saringer 1987
figure 4.12



First generation Toronto Mobilimb, Saringer 1987
figure 4.12

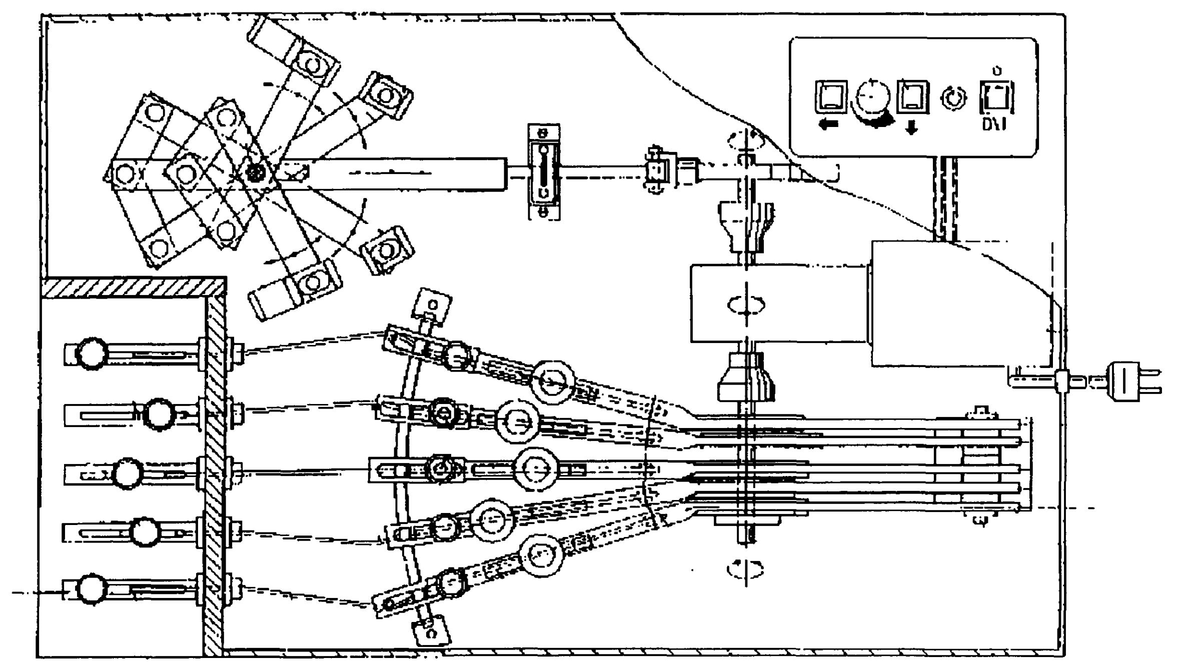
The first generation device was succeeded by the second generation Mobilimb H2 (Saringer 1987, Saringer and Galbreath 1991), shown in figure 4.13. It has many attractive features including robustness, ease of application and aesthetic appearance. It is mounted on a forearm splint and comprises a single actuating rod to move four fingers simultaneously.



Second generation H2 Toronto Mobilimb, Saringer and Galbreath 1991
figure 4.13

The device is battery driven and is therefore completely self-contained. This is a significant feature because other machines frequently have 'umbilical' cords which connect the machine (and hence the patient) to a controller. The machine is readily portable and has low weight. Its length of travel can be altered between 2.5 cms and 10 cms in five steps.

Pasbrig (1982, 1983 and 1991) has developed two generations of tabletop mounted machines, types A5000 and A5100, and the A5000 is shown in figure 4.14. They are particularly worthy of note because they provide finger abduction as well as flexion / extension - the abduction feature is not available in other contemporary devices. The tips of the fingers are placed in small sleeves, which are moved along guide rails. Individual adjustment, in both planes of movement, can be provided for each finger.

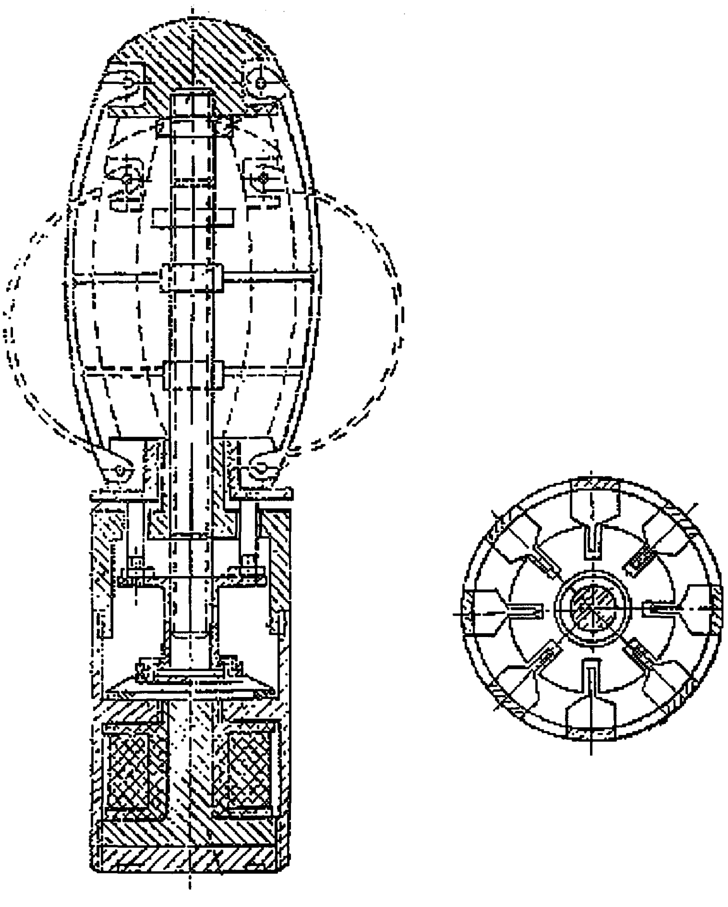


CPM machine type A5000 Pasbrig, 1982, 1983 and 1991
figure 4.14

4.3.3 Expandable and flexible palmar devices

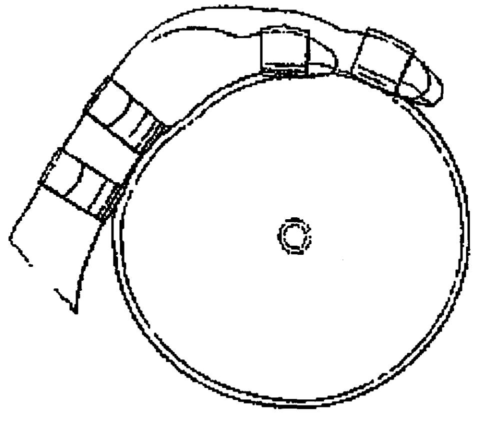
A technically simple design idea is to use a fluid-tight flexible container in the palm of the hand. When the fluid pressure is varied, the container alternatively deflates and expands, causing flexion and extension in the finger joints. This design appears to be particularly suitable for patients with hyperaesthesis or paraesthesia because they provide gentle action and are easy to apply.

Pschenichny and Kucherenko (1974) have described a therapeutic device which comprises an electromagnetically driven elastic balloon placed in the palm of the hand (figure 4.15). The balloon initially has the shape of an ellipse with a high ratio of major/minor axis lengths. Energising the electromagnet increases the length of the minor axis and decreases the length of the major, thereby providing extension of the fingers; similarly the removal of energisation provides finger flexion.

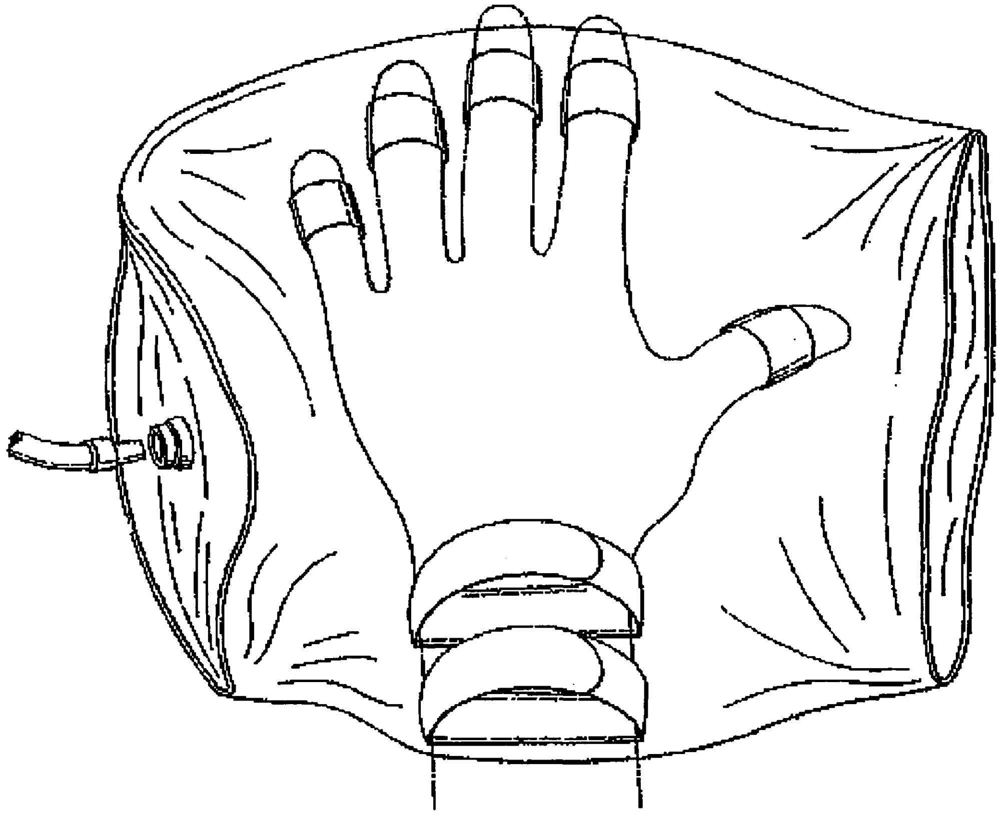


Hand therapeutic device, Pschenichny and Kucherenko, 1974
figure 4.15

Takahashi and Mikiya (1983) have described a device (figures 4.16 and 4.17). which comprises a single air-tight flexible container which includes loops to engage the fingers, thumb, carpus and distal end of the forearm in order to mobilise digital and carpal joints simultaneously. A hand held switch unit has a valve to adjust the airflow rate.

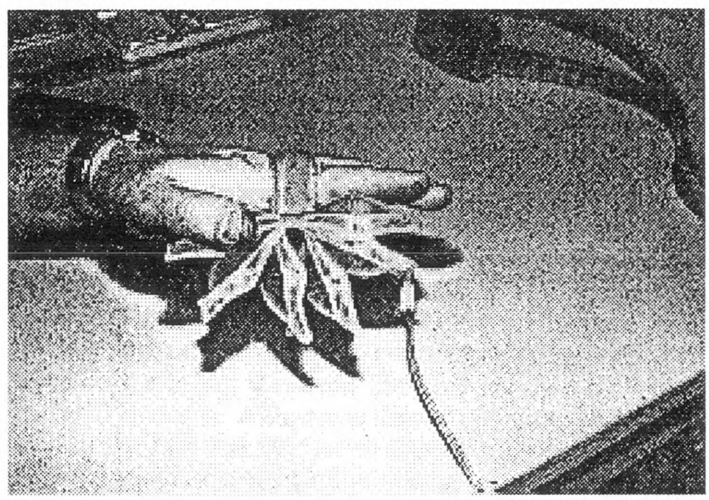


Inflatable therapy device, Takahashi and Mikiya, 1983
figure 4.16



Inflatable therapy device, Takahashi and Mikiya, 1983
figure 4.17

Bentham *et al* (1987) provided a lightweight portable device comprising inflatable bags in the palm of the hand which are ganged together to create the required ranged of motion (figure 4.18). The forces are spread out over the maximum surface area of the hand and because the forces are applied in cycles, adverse pressure effects can be avoided. The disposable bags are fabricated from inexpensive polyethylene moisture barrier sheeting which are inflated between pressures of 4 to 9 kN/m^2. The inflatable portion can extend beyond the index finger and cause abduction of the thumb. As the flexion contracture is overcome, upto three modules may be ganged together for maximum extension though blocking extensor splints may be needed. Pressurised air is provided by a battery powered portable hand unit attached to a waist belt.

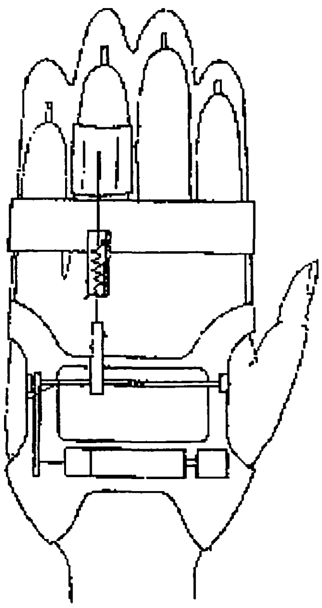


Therapy machine with inflatable bags, Bentham et al 1987
figure 4.18

These types of machines suffer the disadvantage of not being discriminatory in their effect upon individual joints. Indeed, a stiff joint might not be extended at all since the expansion of the container moves the flexible finger joints, not the stiff ones.

4.4 Safety features applied to hand CPM machines

It is obvious that patient safety is paramount whenever a hand CPM machine is applied. General guidelines for the manufacture of medical therapeutic devices are provided in the international standards organisations and (in Europe) the European Community's legal directives. However, no specific standards exist which refer specifically to hand CPM machines and it is currently left to individual designers to provide safety features. For instance, the need to limit the magnitude of the force which can be provided by a machine is obvious. The usual method of sensing load is to monitor the current in a series resistor in the drive motor circuit and to provide an automatic reversal of its cycle when a predetermined magnitude of force has been reached. Zakhidov and Zakhidov (1991) have described a hand CPM machine which includes a load sensor in the transmission rod between the motor assembly situated in the palm of the hand and the connection to the finger tip (figure 4.19).



hand CPM machine with load sensor, Zakhidov and Zakhidov, 1991
figure 4.19

Mechanical stops may also be provided in case of electronic failure (e.g. Yates *et al* 1987, Schenck 1988). There is no conformity in the view of allowing patients to alter the stroke length of hand CPM machines. The Mobilimb systems have obvious external control switches which a patient may use, though the Sutter machine has override facilities so that the patient cannot interfere with the settings provided by the therapist.

4.5 Patient compliance and difficulties in applying hand CPM machines

Clinical treatment by continuous passive motion requires, in the strict interpretation of its meaning, the application of a device for many hours each day and typically for a substantial period. For instance, Ketchum *et al* (1979) treated individual patients with stiff finger joints for four weeks; Bunker *et al* (1989) applied the Toronto Mobilimb for four and half weeks for the rehabilitation of zone II flexor tendon repairs; Bentham *et al* (1987) applied their machine for six weeks to postoperative Dupuytrens patients and for crush and burn injuries. Haimovici (c.1980) applied the Manumobil A5100 machine to patients with a variety of conditions for average durations of four and a half months, with minimum and maximum times of three to nine and half months. No hardfast rules are available concerning the preferred duration of hand CPM machines though it is apparent that protracted use should be anticipated, so patient motivation, machine reliability and design features such as weight, size and ease of application are crucial. It must be accepted that hand CPM is likely to be frustrating for a patient who is inevitably deprived of the functional use of his hand when the machine is applied. Patient-borne machines are highly desirable but paradoxically, they suffer from the disadvantage that in order to mobilise one joint, it may be necessary to immobilise the proximal one, in order to provide a satisfactory means of attaching the machine. Large devices, which can obtain reaction forces from table tops, can avoid the problem of constraining the proximal joint but only with the cost of limiting the patient's personal mobility.

Soeters *et al* (1990) have reported problems of skin pressure at the dorsum of patients' fingers, caused by the Kinetic 8080 machine's fixation block on the distal end of the proximal phalanx. Another frequently reported problem is the difficulty of applying the driving members of the machine to the fingers. Ketchum *et al* (1979) applied the distal ends of the actuating units through small holes drilled in the finger nails or to velcro tags adhered to the nails. They also used gloves in burn injury cases. Mercer (1989) designed an offset hook which is bonded to the nail. Bunker *et al* (1989) reported that devices taped to the finger tips tend to pull off. There is the constant problem that the attachment device for one finger tends to interfere with the attachment of the adjacent finger. The difficulties of providing good fixation should not be underestimated (Blauth, 1992).

4.6 Critique of the review of the clinical application of hand CPM and existing machines

The results of Salter's research on continuous passive motion were demonstrations of its *biological benefits* on cartilage defects, intra-articular fracture models, acutely septic joints and on disorders and injuries of synovial joints. His emphasis on biological benefits ensured that his and Zander's philosophies were quite different. Whereas the Zander machines had ultimately been regarded as crude joint-stretching devices and had lost clinical respectability, Salter's research was successfully transposed to clinical practice. A plethora of CPM machines, especially for the knee, was introduced onto the market and successes were claimed. Besides the knee machines, it was inevitable that attempts would be made to introduce hand machines, no doubt prompted in part by commercial interests. Justification could be made on the grounds that if the so-called 'lively' or 'dynamic' orthoses retain and promote finger joint mobility, surely powered hand CPM machines could do the same? They could also provide tendon gliding, move ligaments, enhance metabolism of joint tissue and resorb effusions. Furthermore, a powered orthosis has an obvious advantage in the treatment of enfeebled patients who might not use conventional non-powered 'dynamic' orthoses. A wide variety of clinical conditions would justify hand CPM, especially injuries to flexor tendons for which consequent hand deformities can be severe and permanent.

In spite of the surge in interest in the application of continuous passive motion which occurred in the 1970s and 1980s, there have been disappointingly few clinical papers concerned with the results of applying hand CPM. The trials which produced statistically significant results were;

(i) A controlled study of the effect of CPM on stiff finger joints provided by Ketchum *et al* (1979)
(ii) The demonstration by Giudice (1990) that the most effective treatment for reducing hand oedema is CPM combined with limb elevation.

The results published for flexor tendon repairs (Bunker et al, 1989, Gelberman et al, 1991) were favourable but it is apparent that hand CPM has not supplanted the Kleinert method for treating flexor tendon injuries. Results for burn injuries (Covey et al, 1988) are also favourable but the control and experimental groups were too small for definitive comparisons.

It is significant to repeat that existing hand CPM machines differ widely in their functionality and operation. It was disconcerting to see their many variations; portable & table-mounted, large & small, easy & complex operation etc. There was certainly a suspicion at the beginning of the research that this wide variation reflected the different attempts to overcome the problems of applying them to patients.

The participating hospitals in Dundee and Berlin had no practical experience in using commercial machines and it was decided that there was insufficient knowledge to chose a particular machine, in preference to another, for this research work. For these reasons, it was decided that CPM machines would have to be built for the research work. Descriptions of these machines, and the methods adopted for attaching them to fingers are provided in chapter 5, sections 5.4, 5.5 and 5.6.

CHAPTER 5

EXPERIMENTAL EQUIPMENT

5.1 Introduction

The review of the clinical literature had shown that the biological benefits of continuous passive motion (CPM) for injured joints had been demonstrated and that the CPM modality had been accepted into clinical practice. It was also clear that CPM for knee rehabilitation was widely used but not CPM for the hand. The review of experimental and commercial hand CPM machines had revealed that there was a wide range of devices available, which varied a great deal in both function and their application to patients.

Discussions were held with clinicians in both Dundee and Berlin and it was agreed that a useful research goal would be an investigation into the role of hand CPM after flexor tendon repair. The deformities that can occur after these injuries may be severe and it was agreed that there was scope for a research programme into the effect of CPM on such issues as tendon movements in their sheaths and the load conditions on healing tendons. In addition, controlled trials could be arranged to compare the results of patients treated with hand CPM with those treated with the established Kleinert method. However, it was decided that such a research programme could not proceed unless the clinicians had full confidence in the application of CPM for the hand. A number of questions were unanswered, for instance;

- Why were there so many different types of machine available?
- Were the machines safe to use? This question had to be posed in spite of the claims made by their manufacturers.
- How long should CPM be applied?

These unresolved questions had a bearing on medical ethical practice and it was decided that it would be unrealistic for the author's research to be directed towards the role of CPM for flexor tendon repairs, though this would be regarded as an important aim for the future. Instead, the primary research aim would be to investigate how CPM affected finger joint range of motion.

The research would have two measurable parameters, namely

- the changes in finger joint angles obtained during treatment, *and*
- the changes in force magnitudes applied by the machine to achieve these changes

Ideally all the patients selected for the research programme would have a common condition, namely Dupuytren's contractures, but there was a limited availability of these patients. Instead patients would have to be selected from a variety of conditions but with the common proviso they had impaired finger joint range of movement and that their clinical assessment showed that there was a good possibility that these ranges would improve in response to CPM. Each patient would be his/her own control.

The trial protocol, developed with the supervising clinicians, made the following stipulations;

- A conservative ('non-risky') approach would be adopted for patient treatment, to minimise risk if the machine behaved in an uncontrolled manner and to ensure patient care would not be jeopardised.
- Trials would be undertaken in hospitals under therapist supervision.
- Patient consent would be necessary, so the trials would have adults only.
- Patient safety would be paramount; the range of machine motion would be limited both electronically (through software) and physically (via mechanical stops).
- The machine should ideally move all finger joints through a complete arc (though this was not achieved until later in the programme).

Both the Dundee and Berlin hospitals had experience of knee CPM but only Dundee had limited experience of hand CPM. For this reason, it was impossible to decide which commercial machine should be purchased for the study because, as stated earlier, no particular product had emerged as a front-runner. In any event, the CPM machine would have to be instrumented, so it was considered preferable to specially develop at least one machine for the research programme.

This research would be worth doing because (i) it would provide data on the magnitudes of forces encountered during hand CPM (ii) knowledge would be acquired on its effect on improving finger joint range of motion for typical finger joint disorders and (iii) the practical difficulties of applying hand CPM would be identified and ideally resolved before CPM could be advocated for flexor tendon repairs.

In summary, the two aims of the project (originally stated in section 1.3) were;

- to study the effect of CPM upon finger joints with limited range of motion (ROM);
- to investigate the development of a prototype CPM machine for the rehabilitation of flexor tendon repairs

It was anticipated that the achievement of the second aim would require use of the practical knowledge and experience gained in meeting the first aim.

To achieve these aims, the following experimental equipment was required;

1) ***Equipment to measure and record hand strength***

The literature review revealed that there was a lack of knowledge about how long CPM should be applied after surgery. Rehabilitation programmes for zone II flexor tendon surgery typically last for six weeks but it cannot be assumed that CPM should be applied for this period. In this research programme, it would have been unsafe (and hence unethical) to apply a CPM machine, which had not been subjected to the test requirements of the Medical Devices Directive (MDD), to patients with recently repaired flexor tendon because of the possibility of rupturing the repair site. Instead, it was decided that CPM could only be applied if two criteria were met, namely; (i) CPM would be expected to lead to reduction in joint swelling and increase in joint ROM, and (ii) there would be minimal risk of injury to the patients in the event of a system fault. Information was needed about the likely period of time CPM should be applied after surgery. It was impractical to assemble patient control groups with a variety of hand conditions, so it was decided to investigate the recovery period of patients after Dupuytrens surgery, *who had not been treated with CPM therapy*, in order to determine the typical hand recovery period. In essence, Dupuytrens patients would be regarded as a general test group for comparison purposes. Although CPM is used for other hand conditions, recovery after Dupuytrens surgery would have similarities in terms of swelling.

Equipment was required to measure and record hand strength because these measurements would be used to assess typical hand recovery periods after surgery.

2) A force transducer for insertion into a CPM machine

The appraisal made at the start of the research programme, of the possibility of studying the effects of CPM treatment upon a typical sample of hand conditions, had exposed the fact that no single commercial machine had emerged as the preferred type for clinical use. On the contrary, the designs of commercial and experimental hand CPM machines varied so widely, it was apparent that no consensus had been reached, regarding the preferred choice of machine design. It was decided to develop a simple push-pull type of machine, within which would be inserted a force transducer that could be used to measure the forces applied by the machine onto patients' fingers. The machine's actuator, force transducer and actuating rod would all lie in the plane of movement (flexion/extension) of a finger so the analysis would two dimensional only. Hence, the force transducer would ideally measure components of force in the horizontal and vertical planes.

3) A twin actuator CPM machine for use in a clinical environment, for tests on a variety of patients with stiff finger joints

The underlying requirement for the test programme was that it should be conducted in a hospital's occupational therapy department, in order to provide realistic data on the application of hand CPM. It proved to be impractical to instrument an existing commercial CPM machine because of the predicted size and complexity of the force transducer. Instead, a purpose-built machine would be required.

It would have been ideal if a CPM machine could have been constructed which had four independently controlled actuators, one for each finger. In practice, an early design appraisal revealed that such a machine would have been too large for use in a hospital clinic. Instead, a compromise decision was made, whereby the machine would have two independent actuators which would be applied to two fingers most severely affected in a patient.

4) A linkage mechanism for finger joint movement

From the outset, it was realised that a finger has three degrees of freedom in the flexion/extension plane but a CPM machine's actuator has only one. There is therefore a kinematic mismatch between the designs of CPM machines and the need to provide full arcuate motion of the finger joints. To overcome this problem it was necessary to develop a linkage that could be attached to a finger, in order to move its joints in a selective manner. This would be particularly important for the future application of CPM to patients with surgical repairs to flexor tendons.

5) ***A single actuator machine which would be used to move finger joints with the linkage mechanism***

   The linkage mechanism described above would have to be evaluated for its suitability for selective mobilisation of finger joints, particularly for patients who had undergone surgical repair to tendons. The linkage would require features to ensure it could be safely used in a clinic, in particular it would need mechanical stops to limit finger joint movement in the event of errors associated with the control processor. Like the twin actuator machine, this machine would need a force transducer and programmable range of movement.

The design of equipment for measuring and recording hand strength is described in section 5.2 and the feasibility study of the design of a three component force transducer for use in a hand CPM machine is described in section 5.3. Section 5.4 describes the development and construction of a dual actuator machine, used to gain technical and clinical experience in the design and application of instrumented machines and for the collection of clinical data. The development of a linkage for moving the joints of a finger is described in section 5.5. The need for this linkage had become apparent during the 'rolling' experimental phase of the research. Finally, section 5.6 describes the single actuator machine, which would be used to move finger joints with the linkage mechanism. This would be regarded as the prototype CPM machine for the rehabilitation of flexor tendon repairs (aim 2).

5.2 Equipment for measuring and recording hand strength

There has been a considerable historical interest in developing methods, which can be used for the objective assessment of the recovery of hand function, in order to quantify in a meaningful manner the relative advantages of various surgical techniques and post-operative regimes. Within the remit of this study, there was a similar need to develop baseline data of the recovery of hand function for a control group of patients which had had surgery for Dupuytren's contracture, followed by conventional post-operative management. The maximum time required for the application of CPM during the period of hand recovery could then be estimated.

Hand function is affected by factors such as dexterity, proprioception, stereognosis and hand strength which are interrelated and difficult to quantify. However, tests for hand strength and finger joint ranges of movement are particularly attractive because it is well known that surgery and joint immobilisation adversely affect these factors. Furthermore, these tests can be undertaken in a clinic and the results are quantifiable. Even a cursory review of the literature reveals that there is an abundance of papers advocating measurements of hand strength and finger joint angles as methods of assessing return of function. However, studies, which use these variables as measures of outcome, have to be verified by statistical validation techniques if they are to attain widespread acceptance.

5.2.1 Review of methods used to measure hand strength - the historical perspective

It is noteworthy that, in an historical context, a large number of hand strength studies have been undertaken upon normal subjects, or patients with particular clinical conditions, to provide baseline data for comparative purposes. A wide variety of dynamometers have been developed, usually employing hydraulic and pneumatic sealed-pressure systems, mechanical (spring) devices, and strain gauge transducers which are illustrated in the following examples. The 'Jamar' dynamometer described by Bechtol (1954) is still in wide clinical use. It incorporates adjustable hand spacing connected to a sealed hydraulic system with a pressure dial. It was used by Swanson *et al* (1970) and by Schmidt and Toews (1970) for studies upon normal adults, by Agers *et al* (1984) for measuring grasp strength of children aged five to twelve, by Bazar (1978) for a study of grip strengths of cerebral palsied adults, and by Kellor *et al* (1971) who provided tables of grip strength norms for clinical use. Another common clinical method of measuring grip strength involves the squeezing of a standard mercury sphygmomanometer cuff normally used for blood pressure measurement. Clawson *et al* (1971) used this method in part of a study of the functional assessment of the rheumatoid hand. Purpose-designed instruments, which utilise inflated bags, include the Boots Grip Strength Meter and the Winthrop Torqometer used by Sheehan *et al* (1983) in their study of hand function for patients with rheumatoid arthritis. In order to obtain an electrical output, Myers *et al* (1980) connected a semiconductor pressure transducer to a sphygmomanometer in a further study of patients with rheumatoid arthritis. An electrical output was also sought by Patterson and Gabbard (1982) who constructed apparatus with a pressure transducer connected to an inflated air hose which is gripped by their subjects. Examples of other dynamometers include the 'Sklar' used by Nemethi (1952) for a study of hand grip in industry; the 'Narranganisett' used by Everatt and Sills (1952) who studied hand strength in relation to stature and anthropometric hand measurements; the 'Geckler and Collins' dynamometer used by Kirkpatrick (1957) who considered grip loss in terms of permanent partial disability; the 'Stoelting' device used by Montoye and Lamphiear (1977) to measure the grip strength of 6000 males and females aged 10 to 69; and the 'Kny-Scheerer' dynamometer used by Lunde *et al* (1972) in their study of grip strength of college women. A number of investigators developed table-mounted apparatus, which can be used to accurately, control wrist and hand position. Examples include Nwuga (1975), Hazelton *et al* (1975) and Dickson *et al* (1972). Strain gauge technology has had an obvious role and has been used extensively. Work by Darcus (1953), Sperling (1980) and An *et al* (1980) involved the use of purpose built apparatus. Berme *et al* (1977) used six component load transducers in a study of finger joint biomechanics. Pronk and Niesing (1981) designed their hand grip dynamometer which used strain gauges in a particular way to provide for accuracy and a wide measuring range. Gillespie *et al* (1983) undertook a comparative study between mechanical dynamometers and electromechanical devices to illustrate the accuracy of the latter.

The majority of these devices, for instance the Jamar dynamometer, sphygmomanometer and inflated air hose, measure hand grip strength provided by all four fingers. This approach has the disadvantage that poor strength in one single finger could be masked by the strength of the other normal fingers. This indicates the need to measure finger strength individually. Furthermore, the strength of an individual finger can vary depending upon the size of the object held and the type of pinch (tip or lateral) or grip position adopted for a test. This variation occurs because of the relative contributions provided by the flexor structures (flexor digitorum profundus, flexor digitorum sublimis *etc*) for varying finger joint angles. These factors have all to be considered in finger strength tests.

5.2.2 Description of hand assessment equipment

The age of many of these papers indicates that the search to obtain a correlated link between hand strength and function has been long-standing. No study was found on the recovery of strength after surgery for Dupuytren's contracture and it was felt necessary to provide statistical data for the recovery of strength for a variety of hand positions. The majority of commercial systems available for measuring hand strength are relatively cheap but rarely have electrical outputs. This would have been a serious limitation in this study because of the need for data acquisition. Alternatively, systems, which do have an electrical output, were prohibitively expensive so it was decided to develop hand assessment equipment with the following specification;

- ***Clinical Assessment.*** The hand assessment system would need to be used in a clinic so all the equipment would be mounted upon a wheeled trolley. Each patient tests would need to be performed in ten minutes.
- ***Hand Position***. It should be possible to use the force transducers in the prehensile functional hand positions described by Landsmeer (1962) and for the pinch position in particular. Previous studies had not given same attention to pinch strength as grip strength because conventional dynamometers were not generally suitable for the pinch position.
- ***Transducer requirements.*** The usual transducer requirements of linearity, sensitivity, repeatability etc would be best met with strain gauged transducers. Pressure systems have inherent problems associated with the non-uniform application of forces upon inflated bags.
- ***Data presentation.*** Clinical situations frequently call for rapid, clear and unambiguous visual presentations of information.

Central to the equipment was a patching switch which could be used to connect any one of six full Wheatstone bridge transducers to a microcomputer. Two of the ports were allocated for *pinch/grasp* and *skin shear* transducers. The first transducer was used for the measurement of tip pinch, lateral pinch and individual finger grasp. The second transducer was used to measure the shearing force exerted between the palmar surfaces of the fingers and the surface of a smooth cylindrical object. A conventional commercial strain indicator which also provided a digital display of force values for calibration purposes energised the transducers. Output from the patching switch was directed to an 8-bit analogue-to-digital converter with a conversion speed of 100 microseconds. The calculated error of the system (difference between indicated monitor force value and the true value, divided by full scale output) was less than 2% for the pinch/grasp transducer and less than 3% for the skin shear transducer. The system's repeatability was determined by noting the monitor values of particular forces applied to each transducer at one-minute intervals over a period of nine minutes. Coefficients of variation (standard deviation of force values x 100/mean) ranged between 0.148 per cent and 1.746 per cent for the pinch/grasp transducer and between 0.066 per cent and 3.5 per cent for the skin shear transducer.

The description of the control group, test protocol and results of patient tests is provided in chapter 6, section 6.3. Descriptions of the system and its application have been published (Carus *et al* 1985, Jain *et al* 1985).

5.3 Design appraisal for the development of a three component force transducer

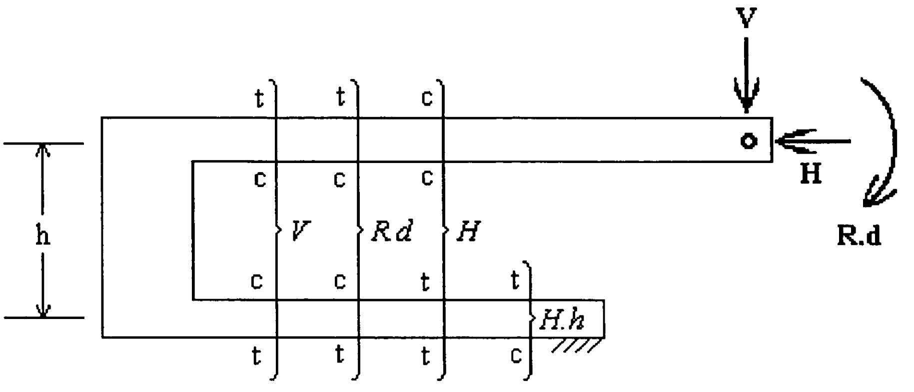
There were two reasons for the measurement of force applied by a CPM machine onto patients' fingers. First, it was necessary to determine how this force varies during the course of treatment and secondly, it had been speculated that an 'intelligent' CPM machine could be developed which could self-adapt its functional behaviour by resetting its ranges of motion in response to a changing force signal. Accordingly, the second item of experimental equipment (after the equipment for hand strength) was a force transducer which could be inserted to measure the forces exerted upon a single finger by a special-purpose or adapted CPM machine. This section describes the feasibility study into the development of a three component transducer, to determine its likely cost, size and complexity.

It had been decided at the outset that the transducer would be inserted into the body of a machine because it would have been impractical to either purchase or design one which was sufficiently small that it could be applied at the end of the actuator rod adjacent to the finger. Two possibilities were considered; first, the transducer could be rigidly fixed to the enclosure of the CPM machine and used to measure the reaction between the enclosure and the actuator mechanism which would be attached to a finger. The transducer would have immobile electrical lead wires and a rigid connection to the machine. This possibility would, however, also incur the disadvantages of requiring a complicated mechanical design to ensure that the force between the moving actuator elements and the frame of the machine were solely transmitted through the transducer. In addition, the transducer might be affected by inertial effects of the moving parts of the actuator mechanism. An alternative possibility would be to attach the transducer at the interface between the output driving point of the actuator and the actuator rod. This would provide the advantage of direct measurement of the load on the actuator rod, without worries of inertial effects. The disadvantage would be the need to provide 'wandering' electrical leads because the transducer would have to be attached to a moving point on the actuator.

The principal differences between the two methods of attaching the transducer would therefore be associated with the method of attaching the lead wires to the transducer body (mobile or immobile leads), the complexity of the mechanical design for inserting the transducer and finally any inertia effects associated with the moving parts of the machine or the patient moving his arm. In either case, the transducer's functional requirements included miniature size, high sensitivity to load, reliability and stability in use.

An appraisal was made of commercial transducers but they were considered to be prohibitively expensive. Instead, a three component transducer was designed and is illustrated in figure 5.1. It would be fitted to the drive for a single finger so an important consideration was the need to minimise its width, so that its presence in the machine would not interfere with the drive for the adjacent finger. A rotated 'U' shaped body was adopted to provide four surfaces to provide the maximum surface area for the application of strain gauges, in order to maximise the signal values. A further advantage of the 'U' shape was the generation of strain on the lower limb by the bending effects of the horizontal component of force, H, applied to the upper limb.

The measurement of the vertical and horizontal components of force could be supplemented by the measurement of the couple R.d, whenever a secondary calculation of the distance, d, between the transducer and the point of application of the force, was desirable. Alternatively, the transducer would be used to measure the force components only, provided its load was applied via a freely hinged pivot.



'U' shaped force transducer - stress states due to loading conditions
figure 5.1

Figure 5.1 shows the tensile, *t*, and compressive, *c*, strains on the upper and lower beams due to the vertical component of force, V, the horizontal component of force, H, and the external couple, Rd, applied to the right hand end of the upper beam.

Since $\varepsilon = \dfrac{\sigma}{E} = \dfrac{Mt}{2EI}$

where t is the thickness of the material
h is the distance between the beams
E is the modulus of elasticity of the material
I is the second moment of area of the transducer beam

then the strains on the surfaces of the upper beam are;

upper beam, upper surface	ε_{axial}	$= \dfrac{(Rd)t}{2EI} + \dfrac{(V)Lt}{2EI} - \dfrac{(H)}{AE}$	- (1)
	$\varepsilon_{transverse}$	$= \dfrac{-v(Rd)t}{2EI} - \dfrac{v(V)Lt}{2EI} + \dfrac{v(H)}{AE}$	- (2)
upper beam, lower surface	ε_{axial}	$= \dfrac{-(Rd)t}{2EI} - \dfrac{(V)Lt}{2EI} - \dfrac{(H)}{AE}$	- (3)
	$\varepsilon_{transverse}$	$= \dfrac{v(Rd)t}{2EI} + \dfrac{v(V)Lt}{2EI} + \dfrac{v(H)}{AE}$	- (4)

and the strains on the surfaces of the lower beam are;

lower beam, upper surface	ε_{axial}	$= -\frac{(Rd)t}{2EI} - \frac{(V)Lt}{2EI} + \frac{(H)}{AE} + \frac{(H)ht}{2EI}$	- (5)
	$\varepsilon_{transverse}$	$= \frac{v(Rd)t}{2EI} + \frac{v(V)Lt}{2EI} - \frac{v(H)}{AE} - \frac{v(H)ht}{2EI}$	- (6)
lower beam, lower surface	ε_{axial}	$= \frac{(Rd)t}{2EI} + \frac{(V)Lt}{2EI} + \frac{(H)}{AE} - \frac{(H)ht}{2EI}$	- (7)
	$\varepsilon_{transverse}$	$= \frac{-v(Rd)t}{2EI} - \frac{v(V)Lt}{2EI} - \frac{v(H)}{AE} + \frac{v(H)ht}{2EI}$	- (8)

where L is the distance between the point of load application and the particular location on the beam where strain would be measured.

5.3.1 Strain gauge layout

Ideally, a layout of strain gauges would be used whereby V, H and Rd could be measured independently of one another. The gauge layout illustrated in figures 5.2 and 5.3 is considered below.

5.3.1.1 Positioning of gauges to measure the vertical component of force, V

The layout of the strain gauges (illustrated in figures 5.2, 5.3 and 5.4) would provide measurement of the vertical component of force by strain separation. Gauges A_{ul} and D_{ul} are wired opposite to one another, as are gauges B_{ul} and C_{ul}. Gauges A_{ul} and D_{ul} are situated adjacent to one another at a distance of L6 from the point of load application and gauges B_{ul} and C_{ul} are adjacent to another at a distance L5 from the point of load application.

from equation 3 (*upper beam, lower surface*);

gauge A_{ul}	ε_{axial}	$= -\frac{(Rd)t}{2EI} - \frac{(V)L6t}{2EI} - \frac{(H)}{AE}$
gauge B_{ul}	ε_{axial}	$= -\frac{(Rd)t}{2EI} - \frac{(V)L5t}{2EI} - \frac{(H)}{AE}$
gauge C_{ul}	ε_{axial}	$= -\frac{(Rd)t}{2EI} - \frac{(V)L5t}{2EI} - \frac{(H)}{AE}$
gauge D_{ul}	ε_{axial}	$= -\frac{(Rd)t}{2EI} - \frac{(V)L6t}{2EI} - \frac{(H)}{AE}$

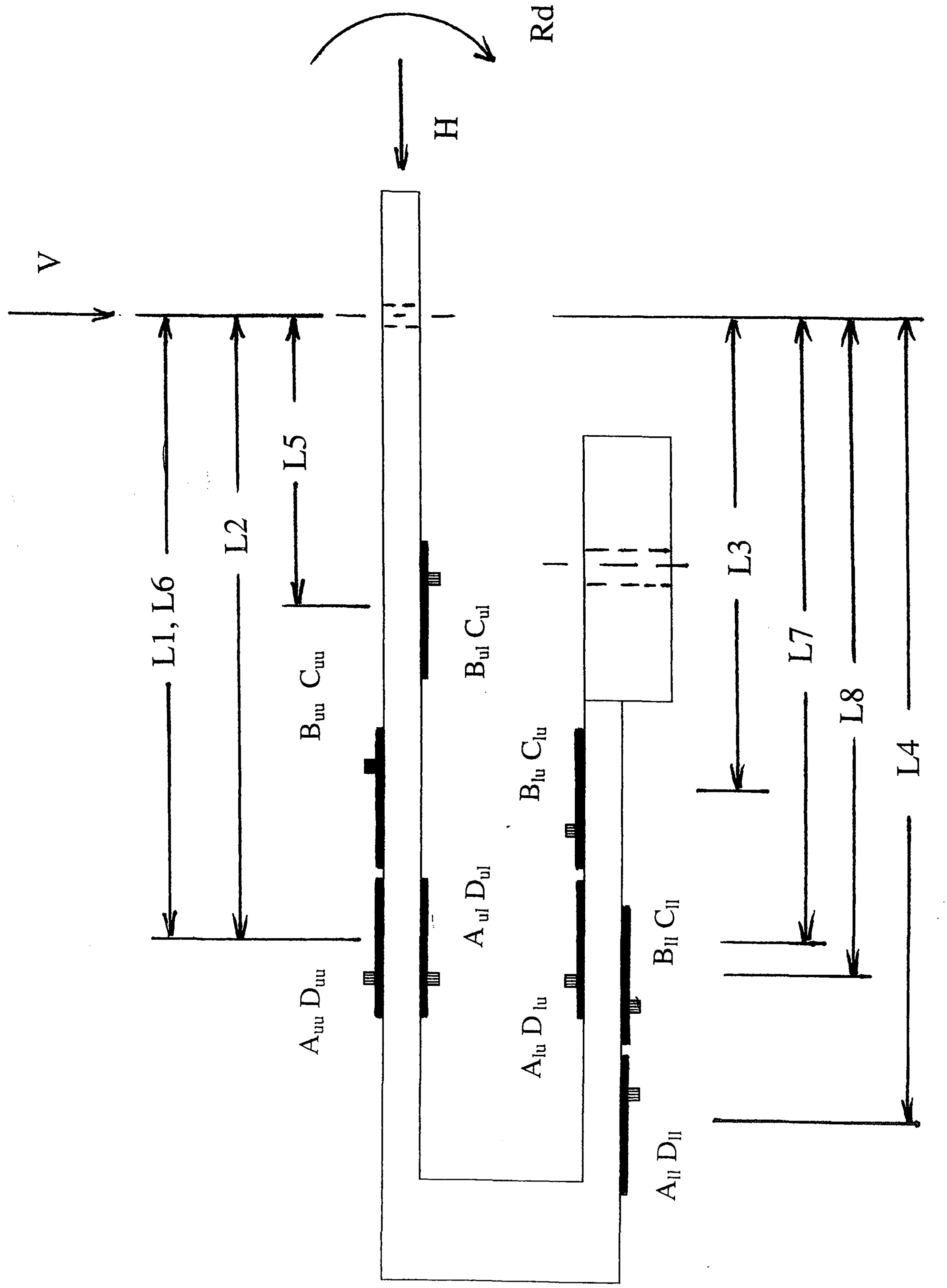
The signal from a full Wheatstone bridge is proportional to;

$$\varepsilon\,[B_{ul} + C_{ul}] \quad - \quad \varepsilon\,[A_{ul} + D_{ul}]$$

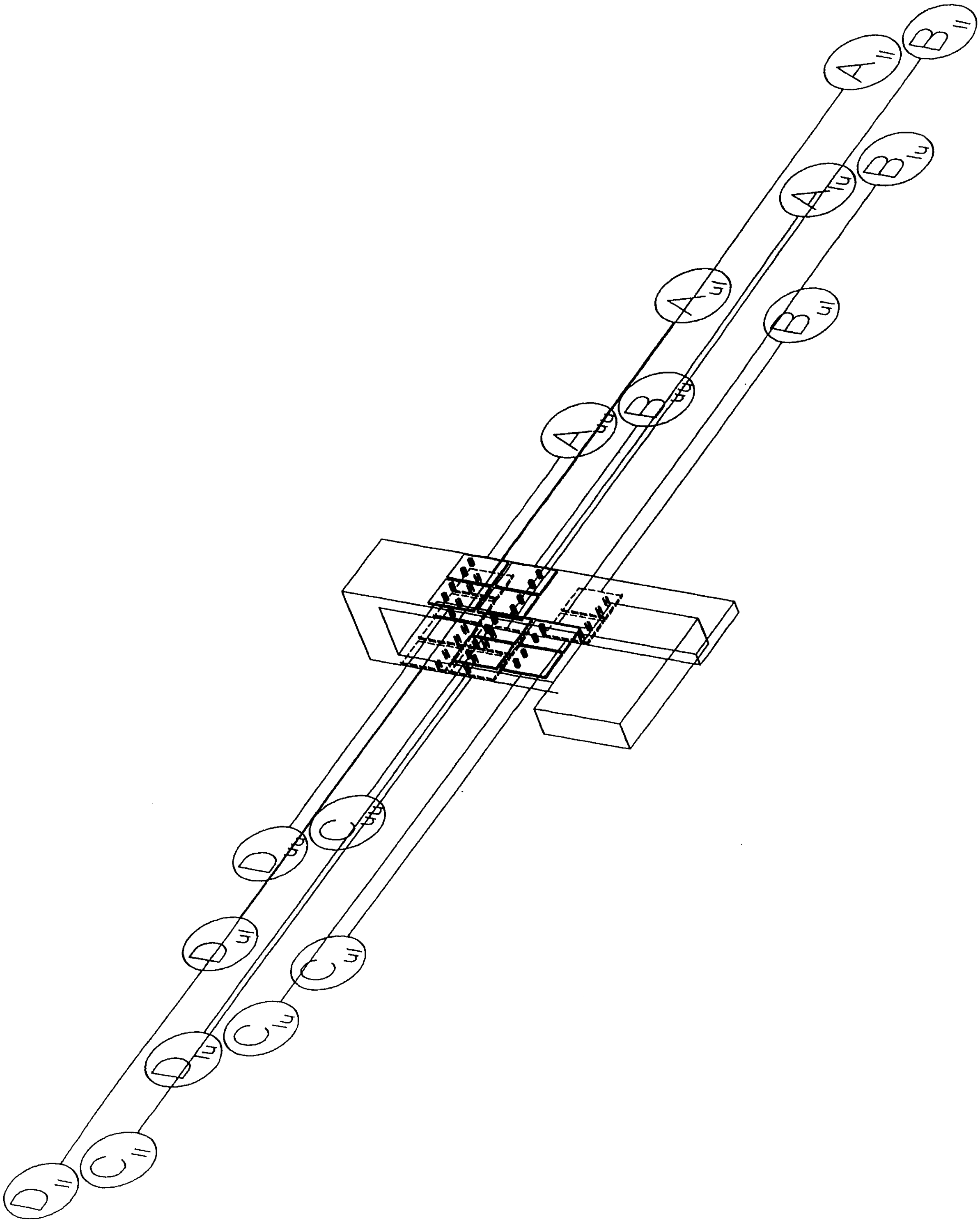
which can be resolved to;

$$\boxed{\frac{(V)\,t\,(L6-L5)}{EI}} \quad - (9)$$

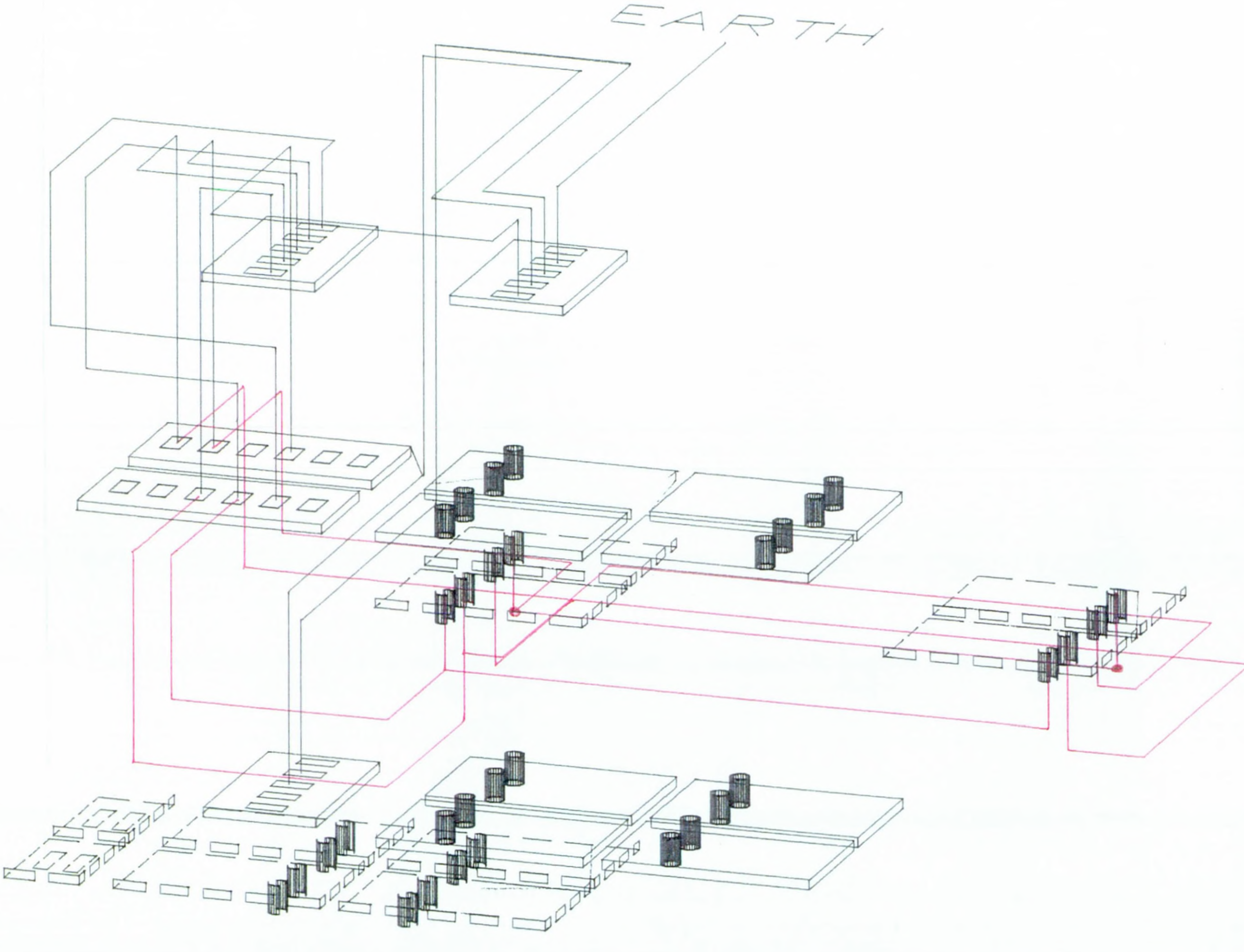
This layout would provide a measurement of the vertical component of load only.



Cross-sectional view of U-shaped transducer, showing the positions of the strain gauges
Figure 5.2



Practical layout of the strain gauges for the U-shaped force transducer
figure 5.3



Practical layout of the wiring for the strain gauges to measure the vertical component of force
figure 5.4

5.3.1.2 Positioning of gauges to measure the horizontal component of force, H

The strain caused by the bending effects, namely the last terms in equations 5 and 7, are the most significant for the measurement of the horizontal component of force, H. Consideration of these equations shows that it is not practical to isolate these terms so instead they have to be maximised. With the layout of the strain gauges illustrated in figures 5.2, 5.3 and 5.5, gauges A_{lu} and D_{lu} are wired opposite to one another as are gauges B_{ll} and C_{ll}. Gauges A_{lu} and D_{lu} are situated adjacent to one another at a distance of L7 from the point of load application and gauges B_{ll} and C_{ll} are adjacent to another at a distance L8 from the point of load application.

from equation 5 (*lower beam, upper surface*);

gauge A_{lu}	ε_{axial}	=	$-\frac{(Rd)t}{2EI} - \frac{(V)L7t}{2EI} + \frac{(H)}{AE} + \frac{(H)ht}{2EI}$
gauge D_{lu}	ε_{axial}	=	$-\frac{(Rd)t}{2EI} - \frac{(V)L7t}{2EI} + \frac{(H)}{AE} + \frac{(H)ht}{2EI}$

from equation 7 (*lower beam, lower surface*);

gauge B_{ll}	ε_{axial}	=	$\frac{(Rd)t}{2EI} + \frac{(V)L8t}{2EI} + \frac{(H)}{AE} - \frac{(H)ht}{2EI}$
gauge C_{ll}	ε_{axial}	=	$\frac{(Rd)t}{2EI} + \frac{(V)L8t}{2EI} + \frac{(H)}{AE} - \frac{(H)ht}{2EI}$

The signal from a full Wheatstone bridge is proportional to;

$$\varepsilon\,[B_{ll} + C_{ll}] \quad - \quad \varepsilon\,[A_{lu} - D_{lu}]$$

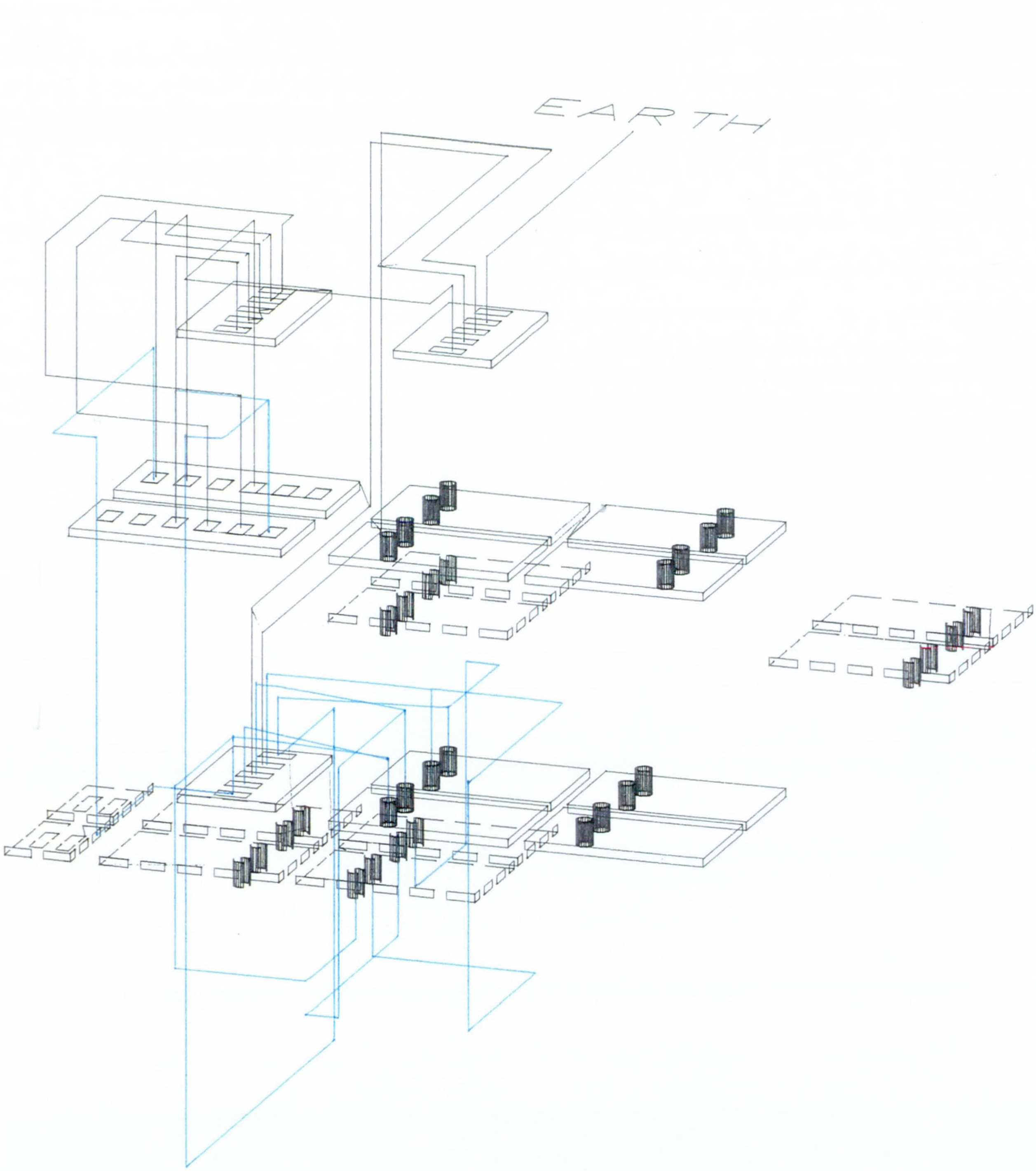
which can be resolved to;

$$\boxed{\frac{2(Rd)t}{EI} + \frac{(V)t(L7+L8)}{EI} - \frac{2(H)ht}{EI}} \quad -(10)$$

The dimension 'h' should be as large as practically possible, whereas L7 and L8 would be as small as possible.

5.3.1.3 Positioning of gauges to measure the moment, Rd

Measurement of the couple, Rd, is complicated by the fact that the strain sign values (tension or compression) on the surfaces of the transducer beams are the same as those for the bending moment terms for VL so they cannot be separated. In order to maximise the



Practical layout of the wiring for the strain gauges to measure the horizontal component of force
figure 5.5

measurement of strain, eight gauges would be used and the bridge would comprise a pair of gauges in each limb of the bridge.

From equation 1 (*upper beam, upper surface*);

$$\text{gauge } A_{uu} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L1t}{2EI} - \frac{(H)}{AE}$$

$$\text{gauge } B_{uu} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L2t}{2EI} - \frac{(H)}{AE}$$

$$\text{gauge } C_{uu} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L2t}{2EI} - \frac{(H)}{AE}$$

$$\text{gauge } D_{uu} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L1t}{2EI} - \frac{(H)}{AE}$$

from equation 5 (*lower beam, upper surface*);

$$\text{gauge } B_{lu} \quad \varepsilon_{axial} = \frac{-(Rd)t}{2EI} - \frac{(V)L3t}{2EI} + \frac{(H)}{AE} + \frac{(H)ht}{2EI}$$

$$\text{gauge } C_{lu} \quad \varepsilon_{axial} = \frac{-(Rd)t}{2EI} - \frac{(V)L3t}{2EI} + \frac{(H)}{AE} + \frac{(H)ht}{2EI}$$

from equation 7 (*lower beam, lower surface*);

$$\text{gauge } A_{ll} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L4t}{2EI} + \frac{(H)}{AE} - \frac{(H)ht}{2EI}$$

$$\text{gauge } D_{ll} \quad \varepsilon_{axial} = \frac{(Rd)t}{2EI} + \frac{(V)L4t}{2EI} + \frac{(H)}{AE} - \frac{(H)ht}{2EI}$$

Depending upon the excitation voltage, the signal from a full Wheatstone bridge is proportional to;

$$\begin{array}{cccc} & \varepsilon\,[A_{ll} + B_{lu}] & - & \varepsilon\,[A_{uu} + D_{uu}] \\ + & \varepsilon\,[D_{ll} + C_{lu}] & - & \varepsilon\,[B_{uu} + C_{uu}] \end{array}$$

which can be resolved to;

$$\left|\frac{(V)t(L4-L3)}{2EI} + \frac{2(H)}{AE}\right| - \left|\frac{(Rd)t}{EI} + \frac{(V)L1t}{EI} - \frac{2(H)}{AE}\right|$$

$$+ \left|\frac{(V)t(L4-L3)}{2EI} + \frac{2(H)}{AE}\right| - \left|\frac{(Rd)t}{EI} + \frac{(V)L2t}{EI} - \frac{2(H)}{AE}\right|$$

simplifying;

$$\boxed{\frac{8(H)}{AE} + \frac{(V)t(L4-L3-L2-L1)}{EI} - \frac{2(Rd)t}{EI}} \quad - (11)$$

The strain associated with the first term could be expected to be small; strain associated with the vertical component of force would be reduced by minimising the value of (L4-L3-L2-L1).

5.3.2 Practical design considerations

An isometric view of the strain gauge layout on the transducer body is illustrated in figure 5.3. The dimensions of the load sensitive element is governed by the size of the preferred strain gauge, namely MM gauge type SK 13-062AP-350 for which the matrix size is 6.4 mm (length) * 4.1 mm (wide). The requirement to make L7, L8 and (L4-L3-L2-L1) as small as possible is balanced by practical considerations of the available space for strain gauge application. By trimming the gauges, the dimensions of the transducer body and the locations of the gauges from the free end would be (in millimetres);

breadth, b	height, t	L1	L2	L3	L4	L5	L6	L7	L8
8	1.5	25.5	19	19	32	12	25.5	25	26

distances refer to the nomenclature in figure 5.2

The distance 'h' between the limbs would be 8 mm. The second moment of area of the cross section is $0.008 * 0.0015^3/12$ m^4, i.e. $2.25 * 10^{-12}$ m^4 and the cross-sectional area is $12 * 10^{-6}$ m^2. The modulus of elasticity for aluminium alloy, E, is $70 * 10^9$ N/m^2, so the EI value is $157.5 * 10^{-3}$ N.m^2. Hence, depending upon the excitation voltage, the expected signals are proportional to the following:

for vertical load, V

$$\boxed{\begin{aligned}&\frac{(V)\,t\,(L6-L5)}{EI}\\ &= 129(V)\end{aligned}}$$

for horizontal load, H

$$\boxed{\begin{aligned}&\frac{(V)t(L7+L8)}{EI} - \frac{2(H)ht}{EI} + \frac{2(Rd)t}{EI}\\ &= 486(V) - 152(H) + 19050(Rd)\end{aligned}}$$

for external moment, Rd

$$\boxed{\begin{aligned}&\frac{(V)t(L4-L3-L2-L1)}{EI} + \frac{8(H)}{AE} - \frac{2(Rd)t}{EI}\\ &= -300(V) + 10(H) - 19050(Rd)\end{aligned}}$$

The transducer signals would be obtained from the matrix expression;

$$\{S\} = [C] . \{L\}$$

where;

the calibration matrix, C, is;

$$\begin{bmatrix} 129 & 0 & 0 \\ 486 & -152 & 19050 \\ -300 & 10 & -19050 \end{bmatrix}$$

the load matrix, L, is;

$$\begin{pmatrix} V \\ H \\ Rd \end{pmatrix}$$

The inverse of the calibration matrix is;

$$\begin{bmatrix} 0.008 & 0 & 0 \\ 0.01 & -0.007 & -0.007 \\ -1.167 \cdot 10^{-4} & -3.697 \cdot 10^{-6} & -5.619 \cdot 10^{-5} \end{bmatrix}$$

It can be seen that cross-sensitivity exists between the signals because the off-diagonal elements are not zero. However, if the transducer were used for the measurement of the vertical and horizontal components of force only, then the 2 *x* 2 matrix has only one off-diagonal non-zero element. The third signal for the moment *R.d* could be used for checking purposes and is not strictly necessary.

Continuing the appraisal for typical loads of V = 10 N; H = 2 N; Rd = 0.3 N.m,

then the 3 *x* 3 load matrix is; $$L = \begin{pmatrix} 10 \\ 2 \\ 0.3 \end{pmatrix}$$

for which the required signal matrix would be;

$$S = \begin{pmatrix} 1.29x10^3 \\ 10.27x10^3 \\ -8.695x10^3 \end{pmatrix}$$

These signal values would be directly related to the magnitudes of the strain gauge signals through the choice of gauge excitation.

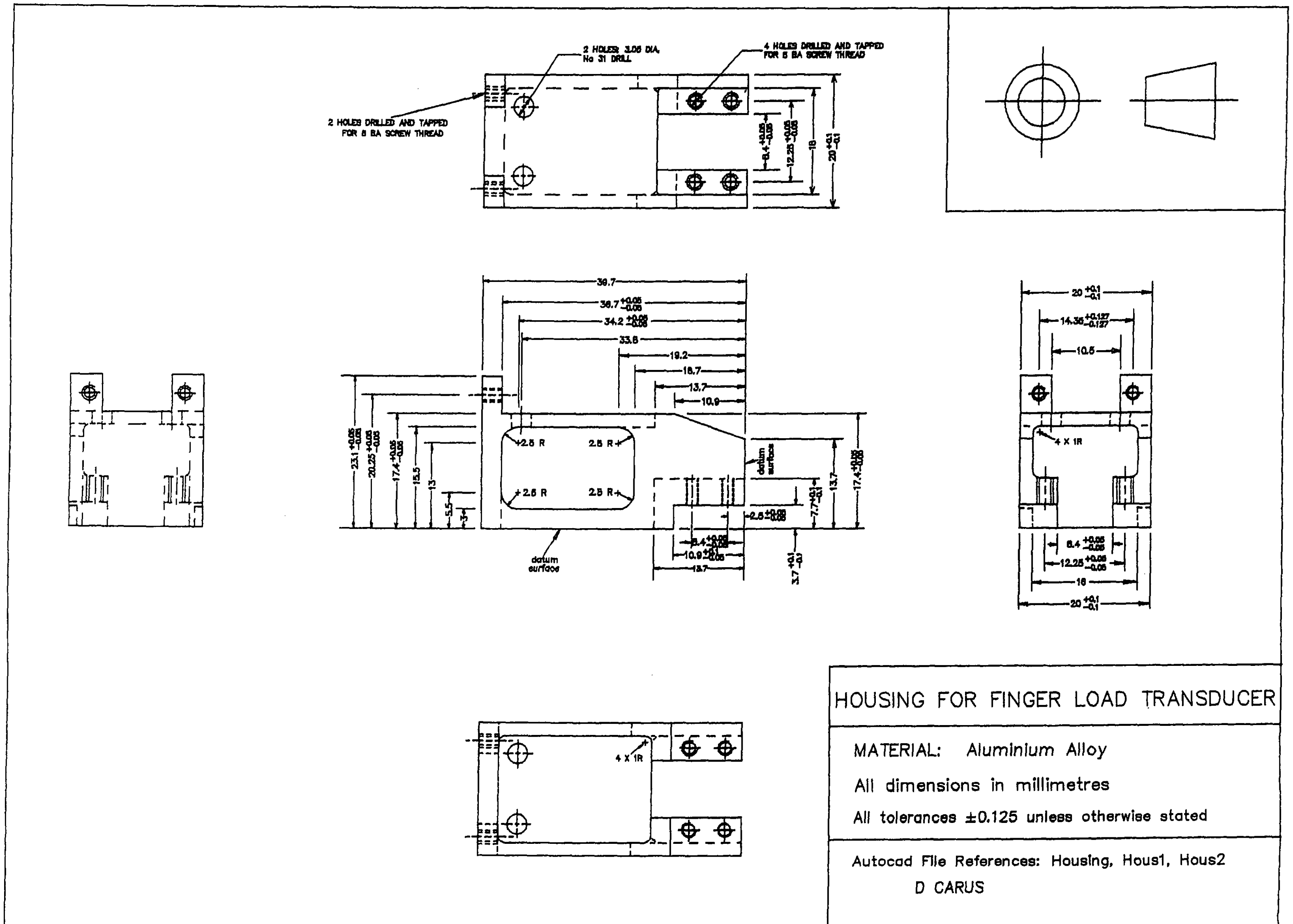
The arrangement for the layout of the strain gauges has the disadvantage that the inverse of the calibration matrix is not only non-diagonal but the magnitudes of the non-diagonal terms have magnitudes comparable to the diagonal terms. Unfortunately, the possibilities for improving or optimising the transducer's characteristics are restricted by the fact that its presence in the machine must not interfere with the actuator for the adjacent finger. This in turn limits its overall dimensions so alternative strain gauge layouts are impractical.

5.3.3 Suitability of the design for practical experimentation

An assessment of the relative advantages and disadvantages of the design was made to assess its suitability for practical experimentation. The principal advantage would be the facility to measure the two force components and, if necessary, a couple, thereby providing accurate measurements in a two dimensional plane. However, there were four severe disadvantages, which are described below.

- The inverse of the calibration matrix is non-diagonal.
- Practical layouts of the wiring for the gauges, illustrated in figures 5.4 and 5.5 for the vertical and horizontal components, are complicated and prompt worries about reliability and maintainability.
- A high level of technical skill would be required for attaching and soldering the strain gauges. Estimates obtained from a commercial company for this task were considered prohibitively expensive.
- There would be a need to provide a protective housing for the expensive transducer. The housing, illustrated in figure 5.6, has a minimum size of 20 * 23 * 40 millimetres which would be significant in the CPM machine.

This assessment culminated in the unfortunate decision not to use the design but instead to adopt a simpler and cheaper design for a single component force transducer, incurring a requirement for an estimate of error inevitably associated with force measurements. Nevertheless, the design of the three component transducer remains on open possibility for the future, particularly if a so-called 'intelligent' machine were developed.



Protective housing for the multi-component transducer
figure 5.6

5.4 Design, construction and functional evaluation of the dual actuator CPM machine

This section describes the design, construction and functional evaluation of a dual actuator CPM machine for the treatment of two fingers. The machine was used and clinically evaluated at the Free University of Berlin.

5.4.1 Functional requirements and specification

The test protocol for the research programme (see section 5.4.6) required the CPM machine to be designed to fit adult patients only. The adults might have a variety of clinical conditions but with the governing criterion that the treated fingers should have some limitation in their joint range of motion. The machine would be attached to the patients' forearms to provide them some personal mobility in the treatment clinic. The functional requirements of the machine would include closed loop position control for pre-selected ranges of motion, in-phase movement of the treated fingers and the ability to measure force exerted by each actuator.

The principal specification data for the machine are listed below;

(i) The design and construction of the machine would meet the broad safety requirements listed in ISO publications. (These were available in summarised form from the Dundee Medical Physics Department for the development of research equipment). The use of the machine would be regarded as *medical treatment* so the appropriate approval would have to be obtained from the medical ethical committee.

(ii) The requirement to fit the machine onto patients' forearms was the limiting constraint for its stroke length. This was set at 100 mm after consideration of anthropometric factors (see section 5.4.2).

(iii) It should be fitted onto a forearm with a flexed elbow and not impede pronation & supination (see section 5.4.2).

(iv) The load transducer should be designed for a direct load of 10 Newtons with a factor of safety of 1.5. (Note: there no was information at the beginning of the research regarding the magnitudes of the forces, which were likely to be encountered so an arbitrary decision was made).

(v) It would be necessary to both measure and record the magnitude of force exerted by the machine onto contracted finger joints.

(vi) The three-component force transducer, described in section 5.3, was regarded as too large to fit into a forearm-mounted machine so a simpler leaf-type design would be used for measurement of bending effects.

(vii) The machine should operate under closed loop position control.

(viii) There was no prior knowledge or published data about the preferred cycle time so it was decided that 15 seconds under no load conditions would be adequate.

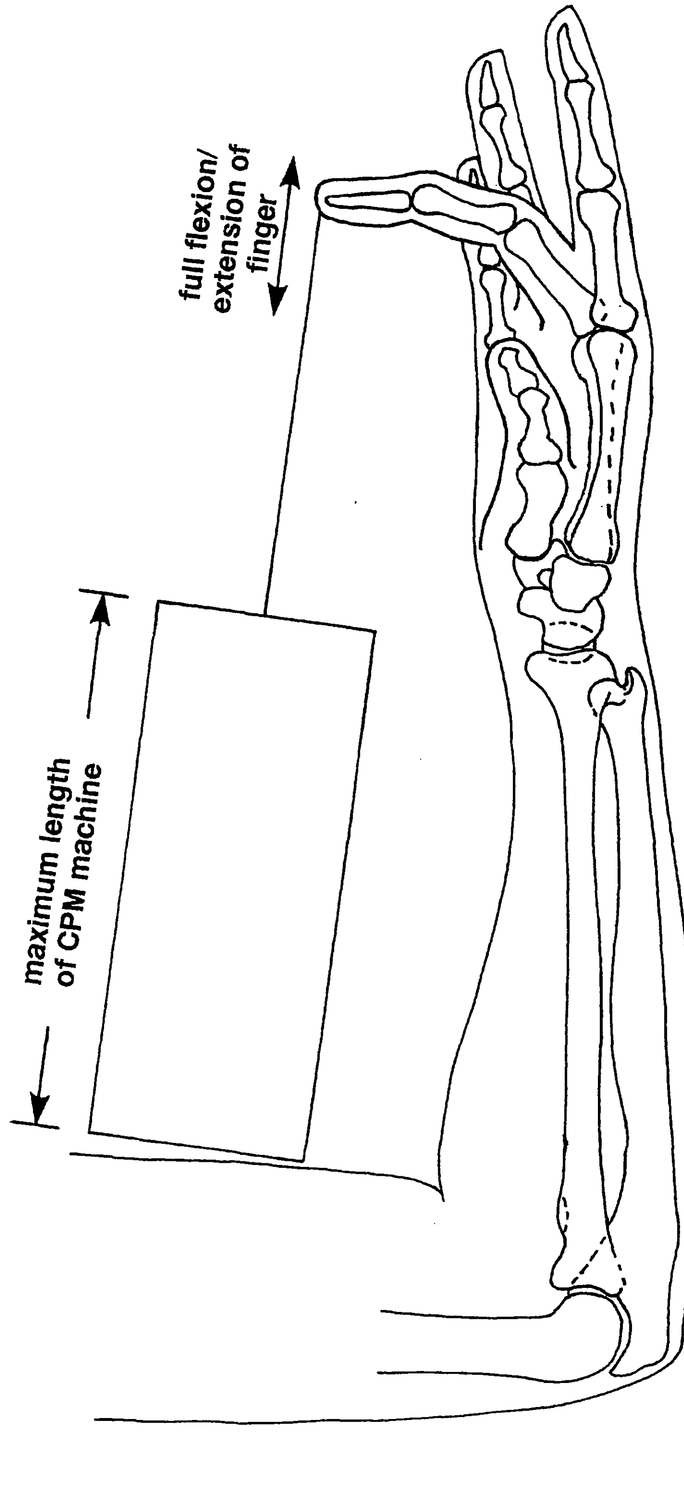
(ix) No lubricants would be used which might entrap dust and fluff and affect the signal from the position potentiometer because this could affect control and hence safety.

5.4.2 Anthropometric considerations for a forearm-mounted CPM machine

There are two anthropometric factors, which influence the size of a forearm-mounted hand CPM machine. First, the maximum length of the machine should ideally be less than the available free length of a patient's forearm, measured from the wrist to the anterior surface of the upper arm when the elbow is flexed, to avoid impeding elbow flexion and pronation and supination when the hand is elevated (figure 5.7 overleaf). This maximum length could be found from relevant anthropometric data. Second, the range of motion of the machine's actuator rods should ideally provide maximum flexion and extension of all three joints of a finger towards and away from the scaphoid. If the actuator rod does not telescope, its length must be reflected in the available stroke length of the machine. This range of motion could only be estimated at the start of the programme but was determined more accurately at its completion.

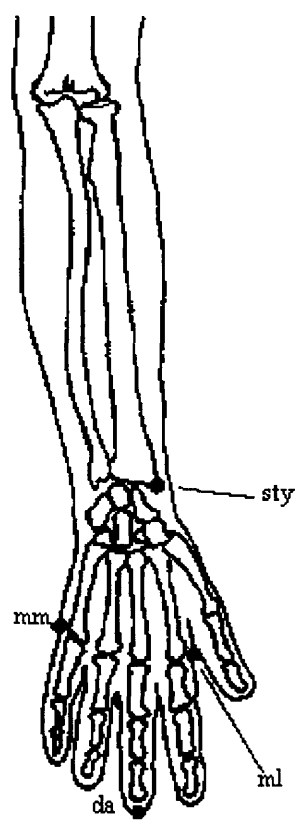
5.4.2.1 Anthropometric data

It is customary ergonomic design practice to provide for 90% of the population, omitting the upper and lower 5% extremes (Singleton, 1978). Whilst there is no clinical reason why the design of the CPM machine should necessarily meet standard ergonometric design criterion, it was considered sensible to ensure that the machine's range of actuator motion and physical



Maximum length of a CPM machine measured from the wrist to the anterior surface of the upper arm when the elbow is flexed
figure 5.7

size would meet this 90% criterion. The obvious approach to this design task would be to determine the bone sizes of an average sized adult and then perform statistical distribution calculations upon population samples, to ensure that 90% of the population could be fitted. The size distribution would have a mean about the 'average' person who would have average sized bones throughout the skeleton. In order to identify this person, Daniels and Churchill (1952) studied a population sample of 4,063 men and showed that a population of this size can be used to identify sets of individuals with average statures, average chest circumference, average arm lengths, etc, but no single individual could be identified who could be matched to each and every set of average data. They concluded that the 'average' person does not in fact exist. To overcome this problem, anthropometric data are often expressed as 5th, 50th and 95th percentiles and the band between the 5th and 95th percentiles is used for design purposes. This approach was adopted in this programme of work. The anthropometric landmarks (figure 5.8) were used in this study, whenever possible, in order to provide standardisation.



Dactylion (da): The distal point of a finger, designated as daI, daII etc. If the dactylion is not stated, it is assumed that the reference point is daIII.

Metacarpale Laterale (ml): The most projecting point on the free outer margin of the hand, at the level of the metacarpophalangeal joint of the little finger.

Metacarpale Mediale (mm): The most projecting point on the free inner margin of the hand, at the level of the meta-carpophalangeal joint of the little finger.

Stylion (sty): The distal margin of the styloid process of the radius where it appears superficially upon the radial side of the wrist. In the hanging arm, it can be felt with the thumb nail when the thumb is moved downwards over the styloid process.

Anthropometric landmarks, Wilder 1920
figure 5.8

Anthropometric data are expressed in two forms, either as absolute lengths between key anatomical landmarks or as proportions of overall stature. The relative merits of both methods to this programme of work are described below.

(i) Forearm and hand length expressed in terms of absolute length

Bailey (1982) collated data published by Garrett and Kennedy (1971), Dreyfus (1967), Woodson and Conover (1964) and by Daniels *et al* (1952), to provide a source reference for systems designers concerned with human performance engineering. The data provided by Woodson and Conover and summarised by Bailey are listed in table 5.1 below.

	Women				Men			
Percentile;	5th	50th	95th	s.d.	5th	50th	95th	s.d.
Hand length	170	183	201	10.2	170	191	206	9.7
Hand breadth	69	76	81	5.1	81	89	97	4.8
Hand thickness	20	25	28	2.5	30	33	36	2.0
Hand circumference	170	183	198	10.2	198	216	236	11.4
Wrist circumference	137	150	163	7.6	157	170	185	8.6
Forearm circumference (flexed)	226	249	274	15.2	259	295	330	21.6
Biceps circumference (flexed)	231	264	307	25.4	277	323	368	27.4
Shoulder to elbow length	284	310	338	15.2	338	368	399	18.5
Elbow to wrist length	211	234	257	12.7	251	287	323	21.3

Anthropometric adult upper limb dimensions (expressed in millimetres)
table 5.1

This method of direct measurement has the attraction of providing precise dimensional data.

(ii) Forearm and hand length expressed as a proportion of stature

Konz (1983) collated the work of Contini (1972), Lewin (1969) and Hertzberg (1963) who expressed anthropometric data as proportions of stature. The relevant heights of anatomical positions from floor level, expressed as proportions of overall body height, are listed in table 5.2;

		Dactylion III (Fingertip) height	Stylion (Wrist) height	Radiale (Elbow) height
Konz	*US*	0.357H	0.485H	0.630H
	Mediterranean	0.371H	0.477H	0.621H
	Nordic	-	0.489H	0.632H

Relevant heights of anatomical positions from floor level, expressed as proportions of overall body height
table 5.2

The first and second columns of data can be used to calculate hand length and hence to provide an estimate of the required stroke length of the machine. The second and third columns of data can be used to calculate forearm length. This method has the disadvantage that knowledge of stature size is required before percentile values of hand and arm sizes can be calculated.

5.4.2.2 Use of anthropometric data to determine the maximum length of a forearm- mounted machine

The free forearm length available for supporting a CPM machine can be estimated by subtracting the radius of the biceps from the distance between the elbow and wrist joints. The method of using body measurements expressed as absolute lengths was adopted to determine the available free length of the anterior surface of the forearm upon which the machine could be positioned. The data published by Bailey (1982) were used (tables 5.3 and 5.4).

	Percentile			
MALE ADULTS:	5th	50th	95th	
Length between elbow and wrist	251	287	323	(mm)
Biceps radius	44	51	59	(mm)
Difference	207	36	264	(mm)

Male adult body measurements expressed as absolute lengths, Bailey 1982
table 5.3

	Percentile			
FEMALE ADULTS:	5th	50th	95th	
Length between elbow and wrist	211	234	257	(mm)
Biceps radius	37	42	49	(mm)
Difference	174	192	208	(mm)

Female adult measurements expressed as absolute lengths, Bailey 1982
table 5.4

The most realistic value of the shortest available forearm length is obtained by using the 5th percentile values for women, for whom the available length is 174 mm (211-37 mm). The most extreme case would be the 5th percentile of the distance between the wrist and elbow joints (to accommodate all adults except 5% of the population whose forearm lengths are so short they cannot be included), less the 95th percentile of the biceps radius (to exclude only those individuals with the broadest biceps). The maximum available length therefore, is 162 mm (211-49 mm) for a woman. The difference between the most likely and most extreme cases is small so the minimum value for the free length of the forearm, which was adopted for design calculations, was 162 mm (6.4 inches).

5.4.3 Construction details of the CPM machine

The machine was designed to fit inside an enclosure of length 160 millimetres in order to meet the maximum length requirement determined above. Furthermore, although the tests of patients' hand strength and rate of return of finger function had revealed the advantage of simultaneously treating all four fingers, the design appraisal had shown it would be impractical to manufacture a machine with four independent actuators because of practical considerations of weight and size. Instead, the machine was designed to hold two actuators for the independent mobilisation of two fingers and fit inside an enclosure sized 160 x 80 x 50 millimetres.

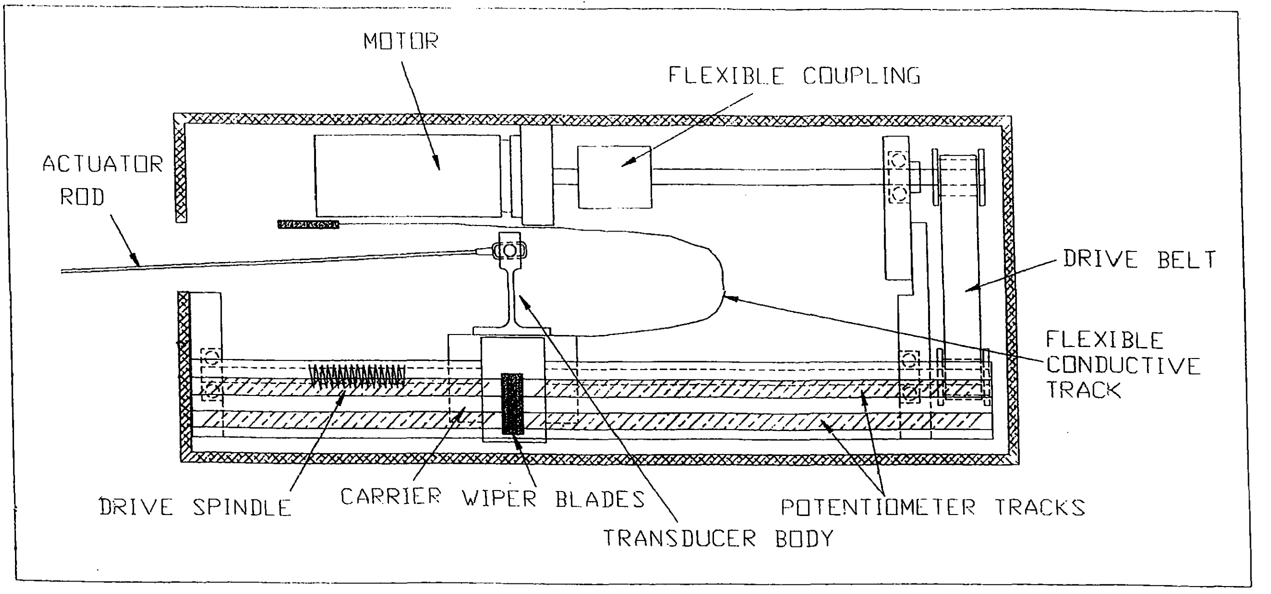
Each actuator was driven by a 12 volt d.c. motor fitted with a gearbox. This rotated a 2 B.A. driving spindle, by means of a belt drive, to provide linear motion to a carrier fabricated from Turcite™. This is a commercial polymeric compound with low friction, self-lubricating and high wearing properties. The carrier rigidly supported a strain gauged beam which acted as the transducer for the measurement of force exerted by the actuator rod onto the finger.

Wiper arms on the carrier brush against a conductive plastic track which was used for continuous position feedback. The track was removed from a commercially available 10K linear potentiometer ('Sakae' model CFL-200-10K). The manufacturers recommended the potentiometer is only used in clean laboratory conditions to safeguard the track. Accordingly, lubricants were avoided because they might have interfered with the potentiometer's electrical output signal, by forming a non-conductive barrier of particles of dirt and wear material trapped in the surface film of lubricant between the electrical tracks of the potentiometer and the wiper arm. If this occurred, the effect might be an interruption in the feedback position control of the actuator with possible danger to the patient.

The load cell was responsive to the bending effect of the direct load applied by the actuator rod. It was manufactured from aluminium alloy type 7017 and designed for a direct load of 10 Newtons which was the maximum the actuator could provide before the motor stalled. Using this design figure, the couple at the strain-gauge area was 10 x 0.0095 Nm. The thickness of the transducer was 1 mm and its breadth 10 mm so using simple bending theory, the magnitude of the stress at the gauges was $6 \times (10 \times 0.0095) / (0.01) \times (0.001)^2$, i.e. 57 MN/m^2 which produced a strain of magnitude $57 \times 10^6 / 68.9 \times 10^9$, i.e. 827×10^{-6}. A safety factor of 1.75 was provided at the location of the gauges. The gauges used were type MM CEA-13-062UW-350.

After preliminary tests were performed on patients, it was realised that the estimated maximum force of 10 Newtons which the machine would apply was in fact too low and forces of 15 Newtons were being encountered. The gearheads of the drive motors were subsequently changed in order to provide a higher force output at the expense of reducing the safety factor. The force calibration characteristics are described in section 6.3.2.3

The CPM machine is illustrated in figure 5.9 and photographs of it applied to a patient are shown in figures 5.10 and 5.11

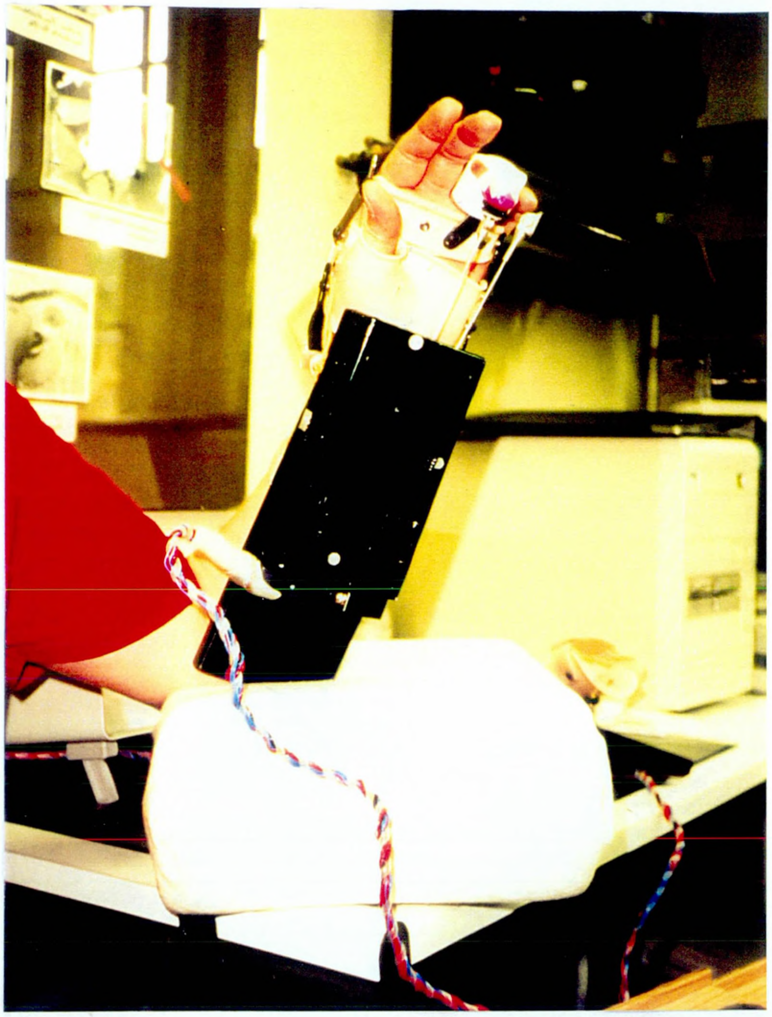


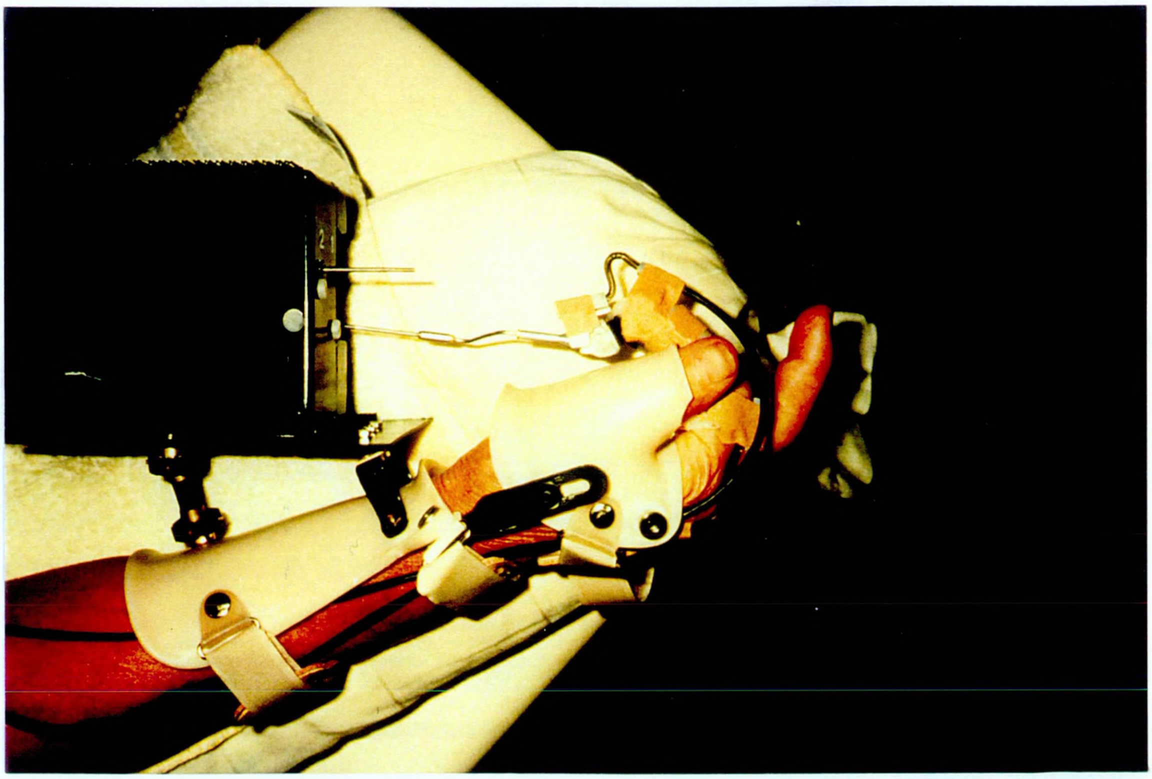
Line drawing of Berlin twin actuator CPM machine
(only one actuator shown)
figure 5.9

5.4.4 Orthosis for the CPM machine

An orthosis was required to immobilise the wrist joint and to support the CPM machine on the volar surface of the forearm. The Steeper-Tayside^{TM} modular upper limb orthotic system was used for rapid application to patients, modified to incorporate rigid connections for the wrist joint. The CPM machine was secured upon a tiltable platform on the orthosis to provide for differing angles of wrist dorsiflexion. The machine was attached to the platform by 3M^{TM} plastic fasteners and orientated such that its actuator rods passed over the patient's scaphoid. This arrangement provided the maximum leverage arm for the generation of moments about the finger joints.

Two methods were used to secure the actuator rods to the finger tips, though both had severe disadvantages. The first method used 3M^{TM} plastic fasteners to attach a plate on the distal end of the actuator rod to a low temperature thermoplastic thimble on the finger tip. The disadvantage of this method was the poor adhesive strength between the fastener and thimble. An alternative method was to use tape to attach the rod directly to the finger tip.





Photographs of the dual actuator CPM machine applied to a patient in Berlin
figures 5.10 and 5.11

5.4.5 Control strategy and system hardware

The aim of the control strategy was to mimic as closely as possible, the natural motion of the fingers. Selectable ranges of finger motion, actuator speed and independent control for each actuator were provided, whilst ensuring the fingers moved in phase with one another. A further facility to stop finger motion at the positions of full flexion and extension, in order to record tissue relaxation at the limits of joint contraction, was also provided. Finally, a 'panic' button was included so that the patient or attendant could stop the machine at any stage.

These requirements were best served by the adoption of a microprocessor based control system which would provide maximum flexibility in the control strategy, without the requirements to redesign analogue control circuit for any new configuration. Use was made of a commercial micro-controller with an Intel 8052AH processor and compatible input/output interface boards. The code was permanently stored on EPROM and configured such that the system would run on power-up. Thus the system could be operated without the need for a VDU screen and keyboard, which was a distinct advantage because the machine was used in a routine clinic.

The control system hardware was designed for closed loop position control with the provision for closed loop force control. The complete system comprised;

- a power supply for the motors, microprocessor, motor control circuit boards, strain gauges, potentiometers and amplifiers
- an 8-bit microprocessor with analogue-to-digital, digital-to-analogue converters and serial communications facilities
- amplifier circuits to drive the motors
- amplifiers for the strain gauges

External switches on the controller were provided to set the speed of the machine and the extents of its travel. Position feedback was measured with the 8 bit analogue to digital converter which gave a theoretical positional resolution of 0.4 mm. In fact, the actual resolution was slightly in excess of 1 mm because of the response time of the controller. Drive power for each d.c. motor was provided by the bi-directional amplifier board, designed such that 0 volts input provided full reverse power and 10 volts provided full forward power to the actuator. The input signal to the driver was generated by the 8 bit digital to analogue converter. Control software for position feedback used one sub-routine to drive an actuator until the set point was reached. Thus it was only necessary to provide a loop which incremented the set point and provided a delay to control the speed of the system. This approach allowed both actuators to be driven without greatly increasing the code size. The control programme was adapted to provide the facility to move finger joints for five minutes then stopping for two minutes before recommencing again. Stress relaxation in the contracted tissue could be recorded during the stationary period. Transducer strain signals were amplified with standard strain gauge amplifiers (RS 308-815). An output port was provided for the acquisition and storage of force and actuator position data from the CPM machine. A personal computer was used because of the large amount of data generated in a typical test; for a relatively slow sampling speed of 1 Hz, the information recorded in a six hour session would be in excess of one megabyte.

Preliminary tests on able-bodied subjects were performed before the device was applied in a clinic. In general, these tests were satisfactory but because the volunteers had no restrictions in their joint range of motion, it was not possible to foresee the difficulties in keeping the actuator firmly attached to the finger tip. These were shown during patient tests and led to the development of the linkage mechanism described in section 5.5.

5.4.6 Protocol for patient tests

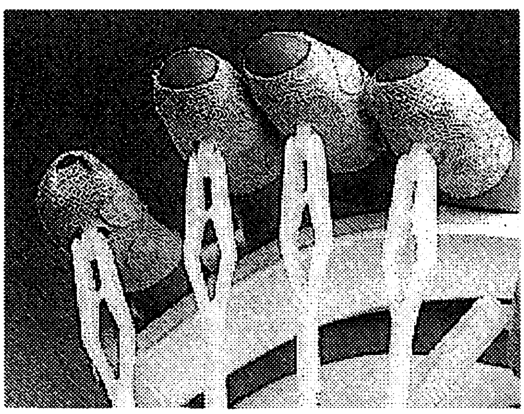
Patients were able to walk in the therapy department whilst the machine was applied but generally they preferred to be seated throughout treatment sessions and they normally opted to support their arms on a table edge. The orthosis was invariably adjusted to immobilise the wrist joint. After the CPM machine had been applied, the therapist determined the range and speed of movement of each actuator before the treatment commenced. A typical treatment session lasted approximately two hours. Details of the limitations in active and passive ranges of joint motion were recorded at the beginning and end of each treatment period.

5.4.7 Requirements for refurbishment and repair

Treatment by CPM requires, by definition, protracted periods of use with the CPM machine. An irritating and recurring problem was machine breakdown and the need for regular general refurbishment. There were two sources of wear which affected the mechanical integrity of the machine. First, wear occurred on the polymeric carrier which had been exacerbated by a lack of parallelism between the lead screw and the carrier support (both rigid structures). The second area of wear was in the motor's gearbox where deterioration in the first gear train and the bearings of the output shaft eventually caused machine failure. The effect of these problems was a requirement to pay considerable attention to the design of the second single actuator machine, to ensure mechanical integrity.

5.5 Linkage mechanism for the movement of a finger

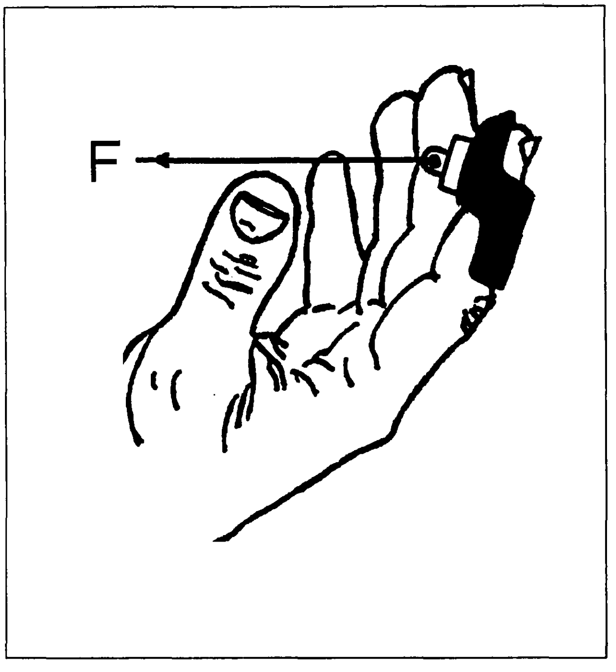
The first method adopted in the clinical trials to attach the CPM machine's actuating rods onto patients' fingers was exactly the same as the method used for the Toronto Mobilimbs. This method used pivot pieces taped onto the finger tips in the manner shown in figure 5.12



Toronto Mobilimb method for attaching actuating rods onto pivot pieces taped onto finger tips
figure 5.12

The early tests quickly revealed a major difficulty that had not been found in tests on normal hands, namely the adhesive tape readily stretched and became detached. This problem was so severe that it was the limiting factor in the successful application of the machine.

An attempt was made to overcome this problem by using a Stack™ thimble splint, modified by riveting a plate onto its volar side for the attachment of an actuator rod, and split longitudinally on its dorsal side so that it could be folded onto the finger (figure 5.13). This method did have the advantage that it provided more skin surface area for the adhesive tape but patients complained that the splint pinched their fingernails and interrupted blood supply, despite radical attempts to trim the splint's edges. Furthermore, the importance of mobilising *all* finger joints to obtain differential movement between profundus and superficialis tendons for flexor tendon repairs had been demonstrated by Slattery and McGrouther (1984), yet the Stack™ splint immobilised the DIP joint. Like the first method, the use of Stack™ splints was abandoned as impractical.

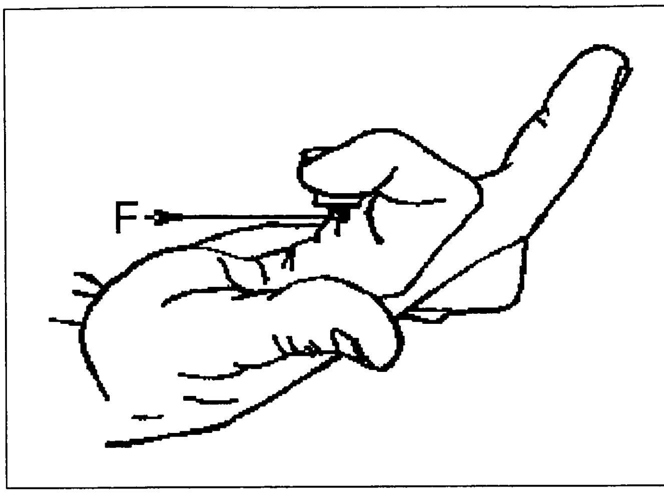


Stack™ thimble splints, modified for the attachment of an actuator rod
figure 5.13

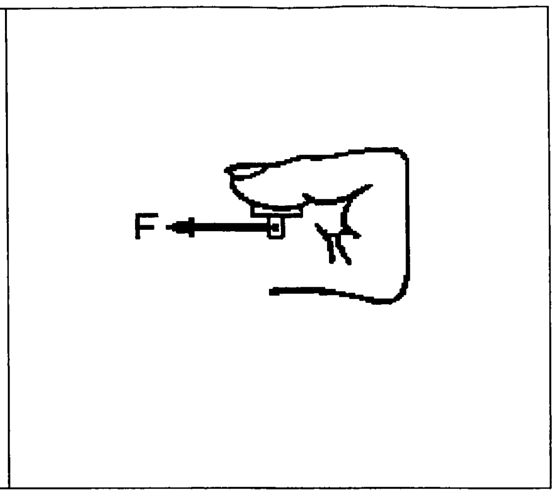
These early clinical trials attracted two clinical criticisms:

1) The application of the pivot plate at the pulp of the distal phalanx meant that the MCP and PIP joints were pushed into extension and the DIP joint into flexion when the machine attempted to extend the finger (figure 5.14). Also, the MCP and PIP joints were pulled into flexion and the DIP joint into extension when the machine attempted to flex the finger (figure 5.15).
2) Because the pivot plate had always to be accessible for the actuator rod, full flexion of the DIP and PIP joints was impossible.

It was decided that the method of attaching an actuator directly onto the distal phalanx was fundamentally flawed and an entirely different method had to be found to attach the CPM machine to a finger.



MCP and PIP joints pushed into extension and DIP joint into flexion – CPM machine pushing the finger into extension
figure 5.14



MCP and PIP joints pulled into flexion and DIP joint into extension – CPM machine pulling the finger into flexion
figure 5.15

On occasions, there would be a need to mobilise a single stiff finger joint but it would generally be incorrect to perform patient tests which provided mobilisation of a single finger joint at the expense of immobilising an adjacent joint. For instance, the results of the study upon the control group of patients with Dupuytren's contractures (later described in chapter 6, section 6.2) had shown that function of the *entire* hand is adversely affected for two months post-surgery. This indicated a need to mobilise *all* the joints in the affected fingers, preferably for *all* four fingers, ideally for this period of time.

It was obvious that the full range of motion of the finger joints could not be achieved unless a means could be developed to (i) overcome the attachment difficulties described above (ii) convert the linear 'push/pull' motion of the CPM machine into arcuate motion for the finger, and (iii) mobilise either a single finger joint, or more typically all three, depending upon clinical need. The kinematic conflict between the three degrees of freedom in finger movement (namely flexion and extension in the three joints), and the single degree of freedom provided by the CPM machine, could be reconciled only if limitations in movement in individual finger joints caused them to behave as locked joints. The majority of patients would not fit this condition, so it was decided to develop a linkage assembly which fulfilled three functions. These were;

- The load would be spread over the three phalanges, not just the distal phalanx.
- The actuating rod must be securely attached to the finger.
- The finger would be moved in an arcuate fashion.

Finally, it was decided that there would be a long-term advantage for future research, to incorporate individual electro-mechanical goniometers on all three finger joints to provide simultaneous joint angle data with CPM force and position data.

There were two types of linkages which could have been developed to meet these aims. First, a kinematically closed mechanism could have been constructed to which a finger would be attached, so the phalanges are redundant 'links' in the mechanism. This type of design is common and is used in the Kinetec™ and Sutter™ machines for instance. The second type of linkage would only become a closed mechanism when applied to a finger. The phalanges would then be essential integral links in the mechanism which would be kinematically unstable when removed from the finger. The latter approach was adopted in this research because it was considered that the first approach might result in a heavy and bulky device.

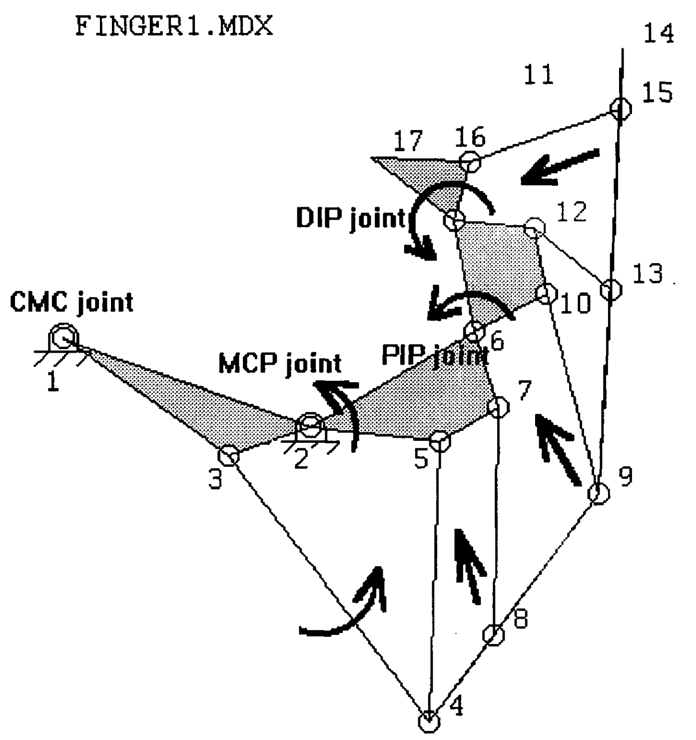
This section describes the design and construction of two linkage assemblies, which fulfilled the three aims listed at the bottom of the previous page. The first, described in section 5.5.1, provides the finger with a single degree of freedom but suffers from the disadvantage of its kinematic complexity. The second, described in section 5.5.2, has two degrees of freedom. It is kinematically simpler and can be adapted to provide a single degree of freedom at any joint or alternatively move all the joints together.

5.5.1 Design of a linkage to provide a single degree of freedom for a finger

A single degree of freedom linkage was designed with DE/Mec mechanism software and is illustrated in figure 5.16 (*finger*1.*mdx*). The linkage is designed to behave as a 'kinematic chain', driven by a single rotating crank. At any instant, the motions of the three finger joints are determined by the angular velocities of the links. The coordinate position of every node in the linkage can be uniquely defined from knowledge of the crank angle and the lengths of the various links in the assembly. Nodes $n1$ and $n2$ are fixed points representing the carpometacarpal and the metacarpophalangeal joints respectively. Nodes $n6$ and $n11$ are the centres of rotation of the proximal and distal interphalangeal joints. Nodes $n5$ & $n7$, $n10$ & $n12$, and $n16$ are pivot points on orthotic components firmly attached to the phalanges.

Nodes $n4$, $n8$, $n9$, $n13$ and $n15$ are situated on links in the assembly. Node $n3$ is the pivot node for the input crank $n3n4$.

With this configuration, nodes $n1n2n3$ represent a structure for which nodes $n1$ and $n2$ are anatomical joints and $n3$ is a pivot point located near to the dorsal surface of the hand within an orthosis. Nodes $n1$, $n2$ and $n3$ have no relative movement. Nodes $n2n5n7n6$ represent a rigid structure comprising the proximal phalanx and an orthotic component taped onto this phalanx. Hence, nodes $n2$, $n5$, $n7$ and $n6$ have no movement with respect to one another. Similarly, nodes $n6n10n12n11$ represent a structure (with no relative movement with respect to each other), namely an orthotic component taped onto the middle phalanx. Nodes $n11n16n17$ represent the fourth structure, namely an orthotic component taped onto the distal phalanx.



Single degree of freedom linkage applied to a flexed finger
figure 5.16

The output node of the crank, $n4$, drives a dyad $n2n4n5$. Nodes $n6$ and $n7$ are rigid offsets to the dyad link $n2n5$ so it can be seen that counter clockwise rotation of the crank results in flexion of the MCP joint. A dyad $n4n7n8$ is constructed upon links $n4n5$ and $n5n7$ such that the intersections of lines joining $n5n7$ and $n4n8$ intersect at a distal point to the hand.

Summary of the actions and functions of the nodes:

*n*1*n*2*n*3, *n*2*n*5*n*7*n*6, *n*6*n*10*n*12*n*11, *n11*n*16*n17 are structures link *n*3*n*4 can pivot about nodes *n*3 and *n*4 link *n*4*n*5 can pivot about nodes *n*4 and *n*5 link *n*4*n*9 can pivot about nodes *n*4 and *n*9 node *n*8 is located in the rigid link *n*4*n*9 and has no relative movement w.r.t. these nodes link *n*7*n*8 can pivot about nodes *n*7 and *n*8 link *n*9*n*10 can pivot about nodes *n*9 and *n*10 link *n*9*n*11 can pivot about nodes *n*9 and *n*15 node *n*13 is located in the rigid link *n*9*n*15 and has no relative movement w.r.t. these nodes link *n*12*n*13 can pivot about nodes *n*12 and *n*13 link *n*15*n*16 can pivot about links *n*15 and *n*16 node *n*14 is located on the rigid link *n*9*n*15 and has no relative movement w.r.t. these nodes

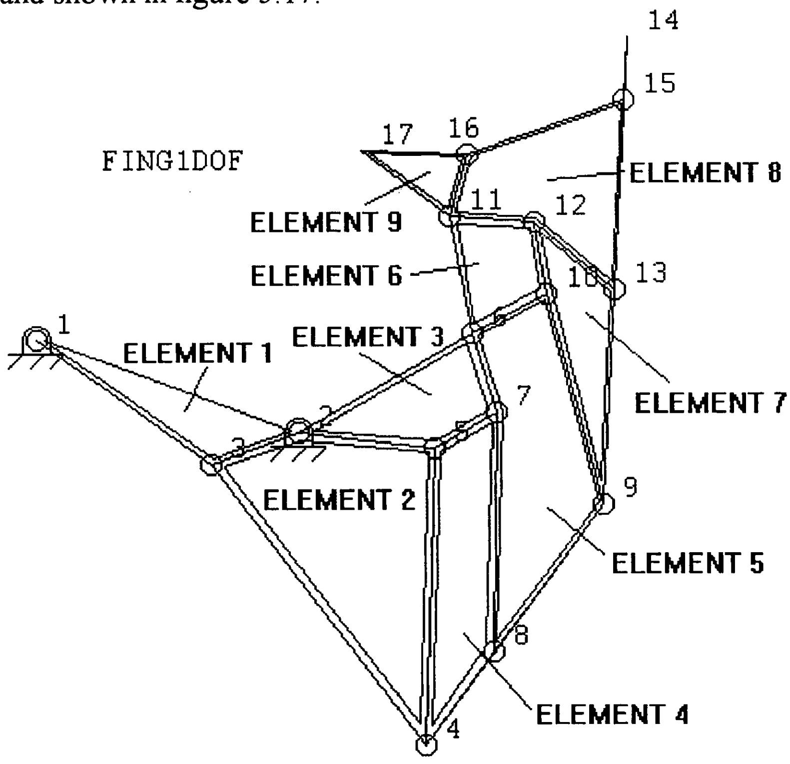
Node *n*9 is a rigid extension on link *n*4*n*8. As the MCP joint flexes, the angle *n*4*n*5*n*7 becomes increasingly obtuse, the distance between nodes *n*5 and *n*8 decreases, so node *n*9 must have a relative velocity towards node *n*6. The movement of node *n*9 towards node *n*6 results in a decreasing angle n6*n*10*n*9 in the dyad *n*6*n*9*n*10. Nodes *n*11 and *n*12 are extensions on link *n*6*n*10 so the movement of node *n*9 towards *n*6 must result in flexion of the PIP joint at node *n*6. As the PIP joint flexes, the angle *n*9*n*10*n*12 becomes more obtuse thereby drawing node *n*13, in the dyad *n*9*n*12*n*13, towards node *n*10. Node *n*15 is a rigid extension upon link *n*9*n*13 which has a relative velocity towards node *n*11 in the dyad *n*11*n*15*n*16. As node *n*15 approaches node *n*11, the angle *n*15*n*16*n*11 becomes more acute, thereby providing a counter clockwise angular velocity of node *n*17, a extension to link *n*11*n*16. The movements of the crank, finger joints and nodes *n*8, *n*9 and *n*15 are illustrated in bold arrows in the diagram.

The linkage has a single degree of freedom so its input movement can be made at any node. For convenience, it could be applied at node *n*14, an extension on the link *n*9*n*13*n*15, where there is access to the linear motion provided by the actuating rod. The entire linkage contains nine interdependently connected elements which comprise the following nodes;

element:	1	2	3	4	5	6	7	8	9
nodes:	*n*1 *n*2 *n*3	*n*2 *n*5 *n*4 *n*3	*n*2 *n*6 *n*7 *n*5	*n*5 *n*7 *n*8 *n*4	*n*6 *n*10 *n*9 *n*8 *n*7	*n*6 *n*11 *n*12 *n*10	*n*10 *n*12 *n*13 *n*9	*n*11 *n*16 *n*15 *n*13 *n*12 & *n*14	*n*11 *n*17 *n*16

Nodes in each of the nine connected elements – single degree of freedom linkage
Table 5.5

The interdependence of these elements is illustrated in tabular form in table 5.6 (*optcheck.xls*) and shown in figure 5.17.



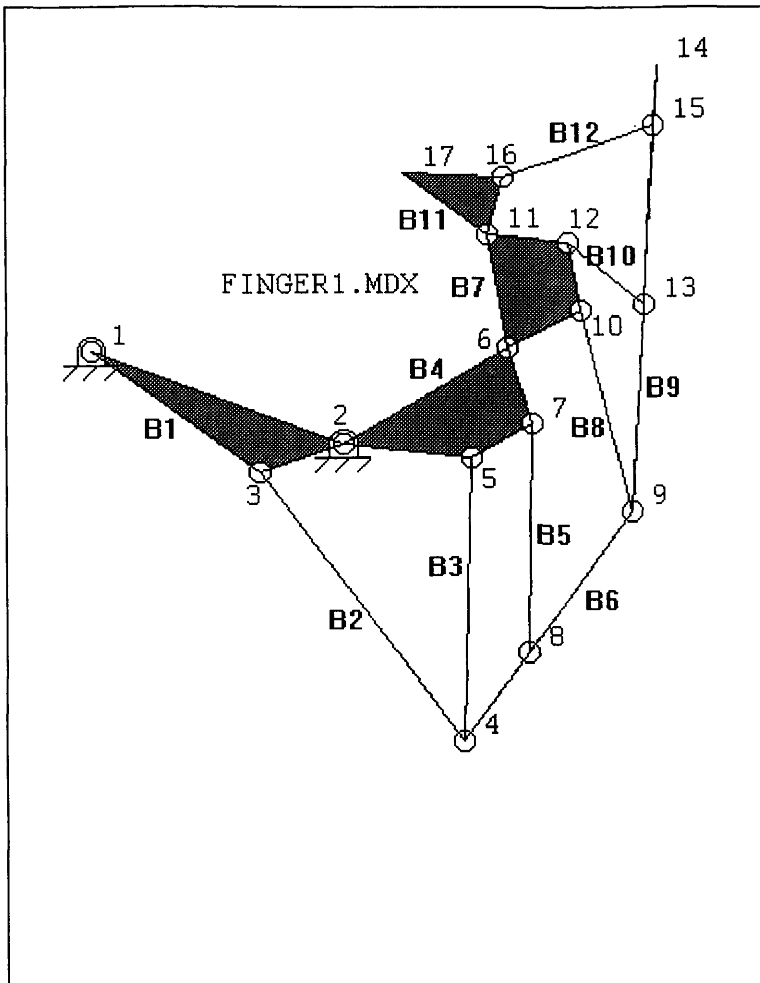
Interdependence of elements winthin single degree of freedom linkage
figure 5.17

5.5.1.1 Kinematic behaviour of the single degree of freedom linkage

The design for the kinematic behaviour of the linkage must provide simultaneous flexion (or extension) of the three finger joints so that the finger tip would close into the palm of the hand in the normal fashion. Alternatively, the 'kinematic chain' could be broken at a convenient point to provide selective movement of one or two joints. The locations of the instantaneous centres of rotation of the PIP and DIP joints about the palm (the 'ground') was found using the three-in-line theorem, namely 'when three bodies are in relative motion, the three instantaneous centres lie on one straight line'. To apply the theorem, the linkage was broken into twelve rigid bodies (B1-B12) illustrated in figure 5.18. For convenience, it can be assumed that motion is achieved by the rotation of the crank, B2. The three-in-line theorem can be applied to (i) determine the centres of rotation of the phalanges about the palm and (ii) predict the angular velocities of the phalanges by equating the angular velocities of the phalanges to the 'moving' crank and hence from the crank to the immobile palm of the hand.

control rovided:	originating node:	mechanism entity:	creates:	in element:	coordinates obtained:	used within mechanism:	construction order for mechanism assembly:
MCP joint	node 3	crank 3-4	node 4	2	X4G Y4G	dyad 2-4-5	3-4 (crank) 4 - 2 -5 (dyad)
	nodes 2 and 4	dyad 2-4-5	node 5		X5b Y5b PHIb2gb X5G Y5G		
	nodes 2 and 5	offset to 2-5	node 6	3	X6b Y6b PHIb3gb X6G Y6G		6 (offset)
	nodes 2 and 5		node 7		X7b Y7b X7G Y7G	dyad 4-7-8	7 (offset)
MCP & PIP joints	nodes 4 and 7	dyad 4-7-8	node 8	4	X8b Y8b PHIb4gb X8G Y8G	offset to 48	4-7-8 (dyad)
	nodes 4 and 8	offset to 4-8	node 9		X9b Y9b X9G Y9G	dyad 6-9-10	9 (offset)
	nodes 6 and 9	dyad 6-9-10	node 10	5	X10b Y10b PHIb5gb X10G Y10G		6-9-10 (dyad)
	nodes 6 and 10	offset to 6-10	node 11	6	X11b Y11b X11G Y11G		11 (offset)
	nodes 6 and 10		node 12		X12b Y12b PHIb6gb X12G Y12G	dyad 12-9-13	12 (offset)
MCP, PIP & DIP joints	nodes 9 and 12	dyad 12-9-13	node 13	7	X13b Y13b PHIb7gb X13G Y13G		12-9-13 (dyad)
	nodes 9 and 13	offset to 9-13	node 15		X15b Y15b X15G Y15G	dyad 11-15-16	15 (offset)
	nodes 11 and 15	dyad 11-15-16	node 16	8	X16b Y16b PHIb8gb X16G Y16G		11-15-16 (dyad)
	nodes 11 and 16	offset to 11-16	node 17	9	X17b Y17b PHIb9gb X17G Y17G		17 (offset)

Mechanism construction for single degree of freedom linkage
(refers to figure 5.17 - FING1DOF.MDX)
table 5.6



B1	the orthosis attached to the meta-carpal; i.e.fixed nodes *n*1, *n*2, *n*3
B2	driving 'crank', link *n*3*n*4
B3	link *n*4*n*5
B4	the proximal phalanx and its attachment block *n*2, *n*5, *n*6, *n*7
B5	link *n*7*n*8
B6	link *n*4*n*8*n*9
B7	the middle phalanx and its attachment block *n*6, *n*11, *n*10, *n*12
B8	link *n*9*n*10
B9	link *n*9*n*13*n*15*n*14
B10	link *n*12*n*13
B11	the distal phalanx and attachment block *n*11, *n*16, *n*17
B12	link *n*15*n*16

Rigid bodies within single degree of freedom linkage
figure 5.18

The following instantaneous centres of rotation are readily identified by inspection:

I_{14} lies at the pivot connecting B1 and B4 (node 2) - the MCP joint
I_{12} lies at the pivot connecting B1 and B2 (node 3)
I_{23} lies at the pivot connecting B2 and B3 (node 4)
I_{26} lies at the pivot connecting B2 and B6 (node 4)
I_{36} lies at the pivot connecting B3 and B6 (node 4)
I_{34} lies at the pivot connecting B3 and B4 (node 5)
I_{47} lies at the pivot connecting B4 and B7 (node 6) - the PIP joint
I_{45} lies at the pivot connecting B4 and B5 (node 7)
I_{56} lies at the pivot connecting B5 and B6 (node 8)
I_{68} lies at the pivot connecting B6 and B8 (node 9)
I_{69} lies at the pivot connecting B6 and B9 (node 9)
I_{89} lies at the pivot connecting B8 and B9 (node 9)
I_{78} lies at the pivot connecting B7 and B8 (node 10)
$I_{7,11}$ lies at the pivot connecting B7 and B11 (node 11) - the DIP joint
$I_{7,10}$ lies at the pivot connecting B7 and B10 (node 12)
$I_{9,10}$ lies at the pivot connecting B9 and B10 (node 13)
$I_{9,12}$ lies at the pivot connecting B9 and B12 (node 15)
$I_{11,12}$ lies at the pivot connecting B11 and B12 (node 16)

Proximal phalanx

The centre of rotation (MCP joint) is easily identified;

I_{14} lies at the pivot connecting B1 and B4 (node 2) - the MCP joint

Knowing I_{12} (the angular velocity of the crank), I_{24} must be found since this provides the angular velocity of the MCP joint.

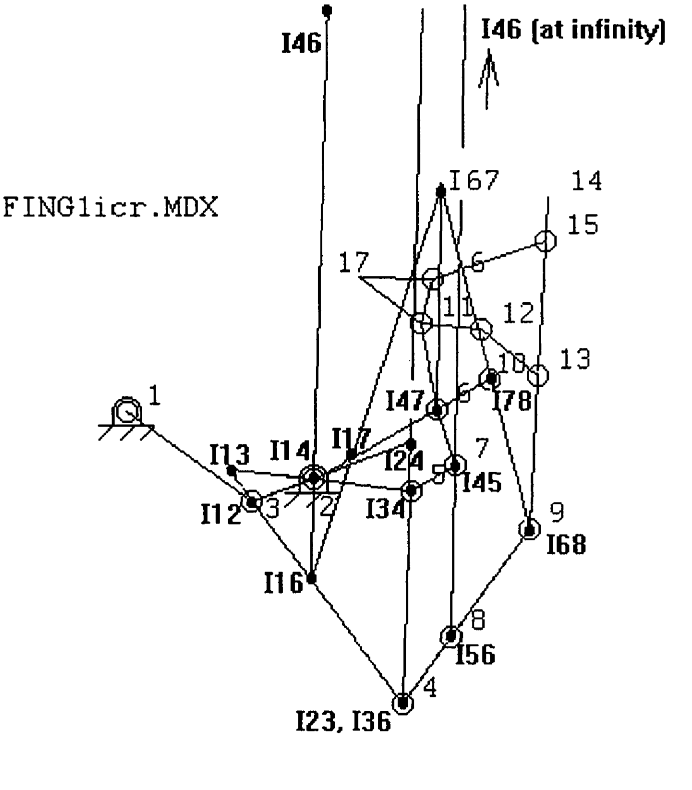
I_{24} lies at the intersection of vectors connecting I_{23} & I_{34} and I_{12} & I_{14}

Middle phalanx

It is required to locate I_{17} at a proximal position to the PIP joint to prevent hyperextension. Using the three-in-line theorem;

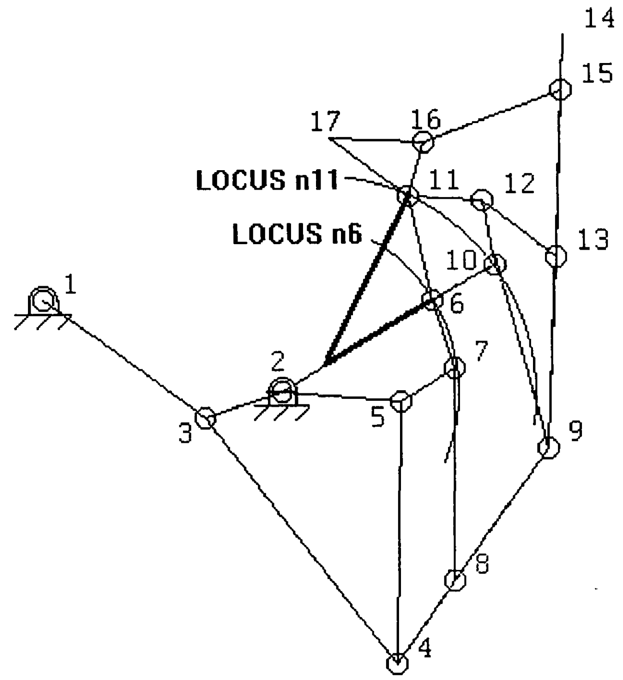
I_{13} lies at the intersection of vectors connecting I_{12} & I_{23} and I_{14} & I_{34}
I_{46} lies at the intersection of vectors connecting I_{45} & I_{56} and I_{34} & I_{36}
I_{16} lies at the intersection of vectors connecting I_{13} & I_{36} and I_{14} & I_{46}
I_{67} lies at the intersection of vectors connecting I_{68} & I_{78} and I_{46} & I_{47}
hence, I_{17} lies at the intersection of vectors connecting I_{16} & I_{67} and I_{14} & I_{47}

The construction is shown in figure 5.19 below;



Instantaneous centres of rotation for single degree of freedom linkage
figure 5.19

Seventeen of the sixty six instantaneous centres of rotation must be correctly positioned in the kinematic chain, in order to fix both the location of the centre of rotation of the middle phalanx (i.e. on the palmar side of the finger) and the angular velocities of the MCP and PIP joints. The nodes which determine these i.c. positions are $n2$ - $n10$ inclusive.
The location of the centre of rotation of the middle phalanx about the metacarpal was confirmed by plotting the bisectors of the loci of movements of the PIP and DIP joints (in DE/Mec *fingericr.mdx*), illustrated in figure 5.20 below.



Centre of rotation of middle phalanx about the metacarpal
figure 5.20

The inter-relationships between these i.c.s. are complex and extremely difficult to formulate in mathematical terms. Instead, two rules can be derived to provide guidance for the positioning of nodes $n2$ - $n10$;

rule 1: When the finger is fully extended, links B3 ($n4n5$) and B5 ($n7n8$) should lie approximately parallel to one another, in order that the centre of rotation of link B6 ($n4n8n9$) about B4 ($n2n5n7n6$ - the proximal phalanx) should lie at infinity. This means that it would be possible to shift nodes $n5$ and $n7$ towards $n2$ (i.e. the linkage could be fitted to a smaller proximal phalanx and hence a smaller hand) without severely disturbing the kinematic relationships affecting the movements of nodes $n4$, $n8$, $n5$ and $n7$.

rule 2: Because the centre of rotation of the middle phalanx about the metacarpal (I_{17}) will always lie on the extension of the vector between the MCP and PIP joints (I_{14} and I_{47}), and must also lie proximally to the PIP joint (to prevent hyperextension), it follows that the intercept of the vector connecting I_{67} and I_{16} with the extension of the vector between the MCP and PIP joints must lie proximal to the PIP joint. I_{16} will always lie on the crank B2 (*n*3*n*4) or an extension to this vector. I_{16} must be positioned proximally to node *n*4 which can be achieved provided the intercept of the vector connecting *n*4 and *n*5 with the vector connecting *n*7 with *n*8, at infinity, lies distally to I_{14} (the MCP joint)

Distal phalanx

It is required to locate $I_{1,11}$ at a proximal position to the DIP joint to prevent hyperextension. Using the three-in-line theorem;

I_{25} lies at the intersection of vectors connecting I_{24} & I_{45} and I_{26} & I_{56}
I_{57} lies at the intersection of vectors connecting I_{45} & I_{47} and I_{56} & I_{67}
I_{48} lies at the intersection of vectors connecting I_{47} & I_{78} and I_{46} & I_{68}
$I_{6,10}$ lies at the intersection of vectors connecting I_{69} & $I_{9,10}$ and I_{67} & $I_{7,10}$
I_{79} lies at the intersection of vectors connecting I_{78} & I_{89} and I_{67} & I_{69}
$I_{8,10}$ lies at the intersection of vectors connecting I_{89} & $I_{9,10}$ and I_{78} & $I_{7,10}$
I_{49} lies at the intersection of vectors connecting I_{47} & I_{79} and I_{46} & I_{69}
$I_{4,10}$ lies at the intersection of vectors connecting I_{47} & $I_{7,10}$ and I_{46} & $I_{6,10}$
$I_{7,12}$ lies at the intersection of vectors connecting $I_{7,11}$ & $I_{11,12}$ and I_{79} & $I_{9,12}$
$I_{9,11}$ lies at the intersection of vectors connecting I_{79} & $I_{7,11}$ and I_{49} & $I_{4,11}$
I_{29} lies at the intersection of vectors connecting I_{26} & I_{69} and I_{27} & I_{79}
$I_{2,11}$ lies at the intersection of vectors connecting I_{29} & $I_{9,11}$ and I_{27} & $I_{7,11}$
$I_{4,11}$ lies at the intersection of vectors connecting I_{24} & $I_{2,11}$ and I_{47} & $I_{7,11}$
$I_{1,11}$ lies at the intersection of vectors connecting I_{17} & $I_{7,11}$ and I_{14} & $I_{4,11}$

Thirty nine of the sixty six instantaneous centres of rotation must be correctly positioned in the kinematic chain, in order to fix both the locations of the centres of rotation of the middle and distal phalanges with respect to the metacarpal (i.e. on the palmar side of the finger and proximal to the respective interphalangeal joint to prevent hyperextension) as well as the angular velocities of the MCP, PIP and DIP joints. The nodes which determine these i.c. positions are *n*2 - *n*16 inclusive. A summary of these thirty nine instantaneous centres is given in table 5.7 on the next page.

	1	2	3	4	5	6	7	8	9	10	11	12
1		MCP PIP	PIP	MCP PIP DIP		PIP	PIP DIP				DIP	
2			MCP PIP	MCP DIP	DIP	DIP	PIP DIP		DIP		DIP	
3				MCP PIP		PIP						
4					PIP DIP	PIP DIP	PIP DIP	DIP	DIP	DIP	DIP	
5						PIP DIP	DIP					
6							PIP DIP	PIP DIP	DIP	DIP		
7								PIP DIP	DIP	DIP	DIP	DIP
8									DIP	DIP		
9										DIP	DIP	DIP
10												
11												DIP
12												

Summary of the thirty nine instantaneous centres of rotation required to orientate all three finger joints
table 5.7

It had been shown that rules could be developed to arrange for the orientation of the links to provide coordinated movement of the MCP and PIP joints. However, it was concluded that the inter-relationships between the links' instantaneous centres of rotation, to provide coordinated movements of the MCP, PIP and DIP joints were too complex for the formulation of rules.

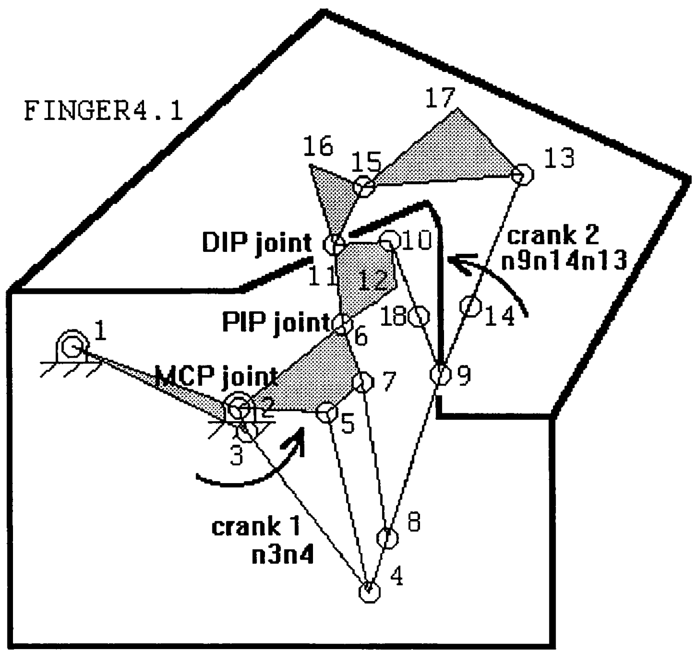
Attempts to provide coordinated movement for all three finger joints by intuitive 'guesswork' were unsuccessful, which was not surprising since thirty nine instantaneous centres of rotation were involved. Instead, attempts were made to optimise the linkage performance by using (i) the Monte Carlo optimisation feature in the commercial DE/Mec software and (ii) an iterative process with software written to model the kinematic behaviour of the linkage (described in section 5.5.4, Computer modelling of the finger linkage mechanism). For both software programs, three sets of targets were set namely the finger joint angles for full flexion, the 'resting position' and full extension. Unfortunately, these optimisation attempts were unsuccessful. Even if an optimised arrangement for the links to move all three finger joints could have been found (and there was little confidence that the attempts would have been successful), the time spent on the optimisation process was deemed prohibitive for this research programme. Both programs were left to run for weeks without interruption and only minimal adjustments in the linkage were obtained.

It is worth stating that, in fact, optimisation was eventually obtained to optimise the linkage for moving the MCP and PIP joints (but not the MCP, PIP and DIP joints together) and the results are described in chapter 7, section 7.4 (improvements in finger linkage mechanism). Unfortunately, these improvements were obtained too late in the research programme to be implemented.

In order to maintain progress, a compromise solution had to be adopted. It was decided that the 'kinematic chain' (figure 5.16) would be suitable for the MCP and PIP joints but not for the DIP joint, so a simpler two degree of freedom linkage would have to be used instead. The portion of the original single d.o.f. linkage design for movements of the MCP and PIP joints was retained but the portion for the DIP joint was replaced by a separate crank & dyad mechanism. The mis-match of moving a two d.o.f. linkage with a single d.o.f. actuator was resolved by including additional links which were normally redundant but could be used to lock the movement of sections of the mechanism, to provide a single d.o.f. linkage with restricted ranges of movement, whenever this was required for a particular patient.

5.5.2 Design of a linkage to provide two degrees of freedom for a finger

DE/Mec model *finger4.mdx*, illustrated in figure 5.21 was developed as a two degree of freedom linkage, comprising two cranks and four fixed length dyads. The first d.o.f. is illustrated in the lower boundary and the second d.o.f. in the upper. Crank *n3n4* controls the movement of both the MCP and PIP joints (the first degree of freedom), whereas crank *n9n14n13* controls the DIP joint (the second degree of freedom). Angles *n6n2n1*, *n11n6n2* and *n16n11n6* are the MCP, PIP and DIP joints respectively. Pivots *n5*, *n7*, *n10*, *n12* and *n15* are located on the orthotic components taped onto the three phalanges. Nodes *n1* - *n9* inclusive have exactly the same functions in the linkage as for the single degree of freedom linkage illustrated in figure 5.16. The connection from node *n*9 to the rigid body *n*6*n*12*n*10*n*11 could have been made from *n*9 to *n*12 (like the previous linkage) but was in fact made from *n*9 to *n*10 for practical considerations in the construction of the linkage. Nodes *n*11 and *n*12 are fixed extensions on the link *n*6*n*10. The crank *n*9*n*13 is the second crank whose centre of rotation is *n*9. The dyad *n*11*n*13*n*15 makes the kinematic connection between the second crank and the DIP joint. Node *n*16 is an extension on the link *n*11*n*15 representing the distal end of the distal phalanx. Node *n*17 is an offset on link *n*13*n*15 so *n*13*n*15*n*17 is a rigid body to which to the CPM machine's actuator arm is attached.



Two degree of freedom finger linkage
figure 5.21

Finally, node *n*14 (which is a fixed extension of the crank) and node *n*18 (a fixed extension to link *n*9*n*12) are provided to attach the additional link to 'lock' the second crank to the movement of the first, thereby creating a single d.o.f. system.

The disadvantage of the two degree of freedom linkage is its unpredictable behaviour when it is subjected to a single force action. Perhaps surprisingly, its clinical tests were successful and it was found that it was possible to apply the linkage to a patient's finger because contracted tissue at the DIP joint provided force transfer between the two degrees of freedom. It is, however, inevitable that no fixed relationship can exist between the DIP joint angle and the PIP & MCP joint angles. In order to provide this relationship, the linkage could be converted into a single degree of freedom mechanism, by mechanically connecting appropriate links whilst keeping the other joints immobile. Two examples of these facilities are described below.

5.5.2.1 Conversion of the linkage from a two degrees of freedom linkage to a single degree of freedom for the DIP joint

Immobilising crank *n3n4*, by locking it in a fixed position with respect to the metacarpal, prevents movement of the MCP and PIP joints. The kinematic behaviour of the second crank acting on the DIP joint is illustrated in figure 5.22. Full flexion and extension of this joint can be provided because the mechanism is simple to optimise.

5.5.2.2 Conversion of the linkage from a two degrees of freedom linkage to a single degree of freedom for the MCP joint

DE/Mec model *finger5.3.mdx*, illustrated in figure 5.23 is geometrically similar to *finger6.mdx* (illustrated in figure 5.22, except for two differences;

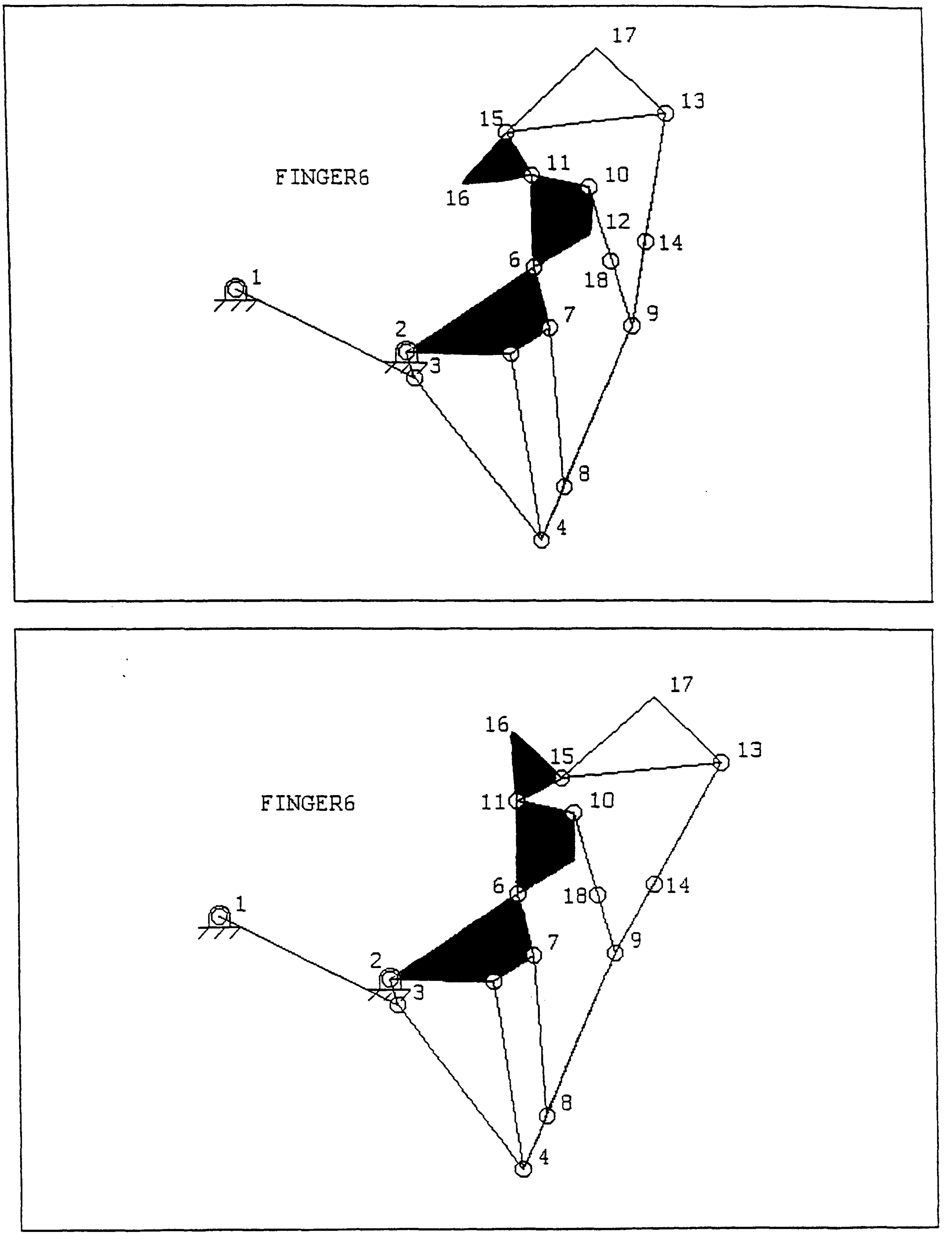
- The length of link *n7n8* has been shortened, thereby breaking rule 2 (section 5.5.1.1, page 125). The effect is to dislodge the position of I_{46} and hence the position of I_{67} (figure 5.19, page 123)
- A rigid connection is made between nodes *n*13 and *n*14 (previously *n*14 and *n*18) *NB;* the node numbers are automatically generated by the software.

The connection between nodes *n*13 and *n*14 eliminates movement of the secondary crank *n9n*15 and because there is *almost* no movement of node *n*9 towards node *n*6, nor node *n*15 towards *n*11, there is almost no movement in the PIP and DIP joints. The relationships between the positions of the nodes can be determined by regarding the linkage as comprising seven elements which comprise the following nodes;

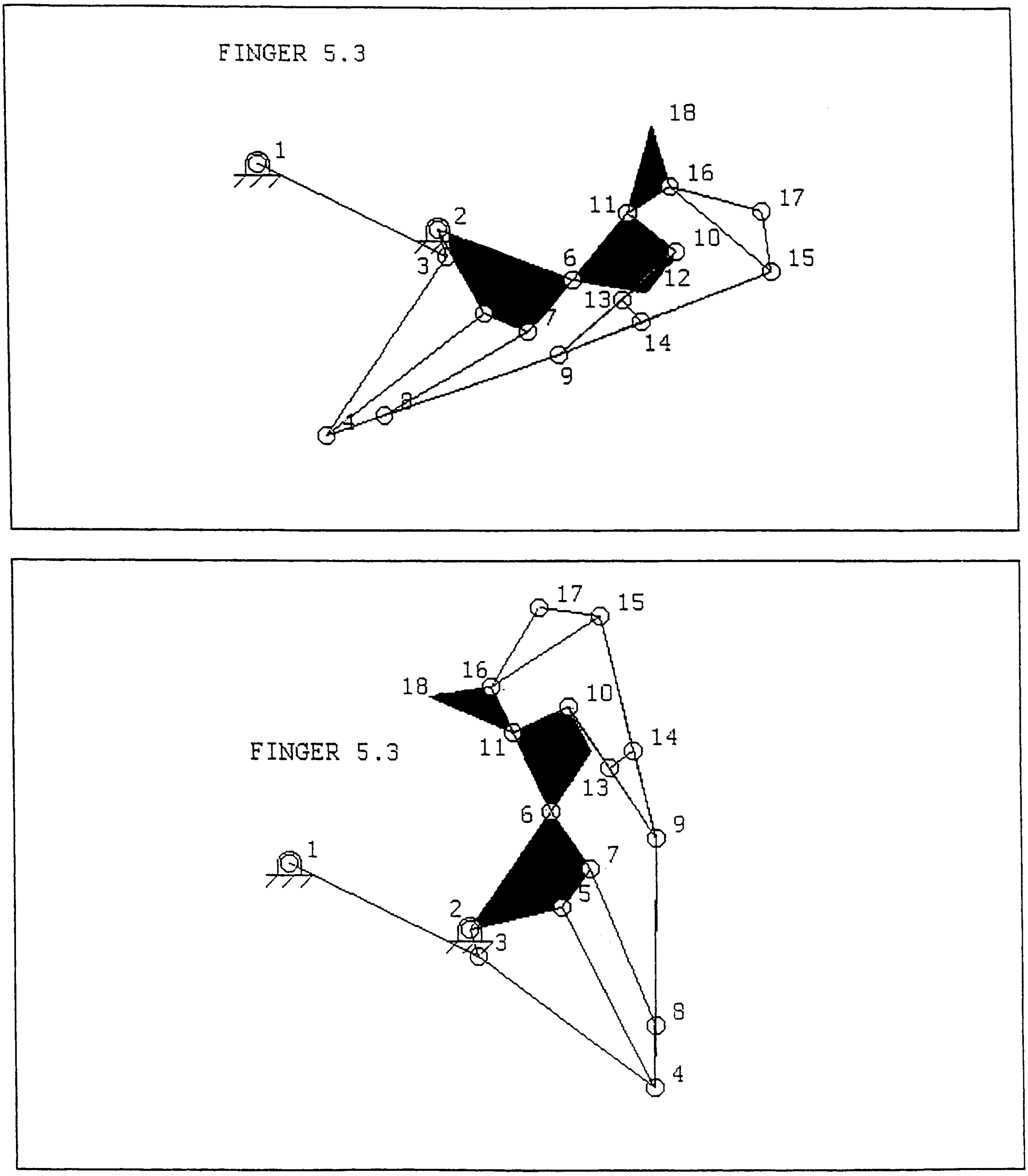
element:	1	2	3	4	5	6	7
nodes:	*n*1*n*2 *n*3	*n*2 *n*5 *n*4 *n*3	*n*2 *n*6 *n*7 *n*5	*n*5 *n*7 *n*8 *n*4	*n*6 *n*10 *n*9 *n*8 *n*7	*n*6 *n*11 *n*10 *n*12	*n*9 *n*10 *n*11 *n*18 *n*16 *n*17 *n*15

Nodes in each of the seven connected elements – linkage for MCP and PIP joints
Table 5.8

The interdependence of the nodes in the seven elements are illustrated in table 5.9



Kinematic behaviour of the second crank acting on the DIP joint
figure 5.22



Two d.o.f. linkage converted to single d.o.f. linkage by the addition of link n13n14
figure 5.23

control provided:	originating node:	mechanism entity:	creates:	in element:	coordinates obtained:	used within mechanism:	construction order for mechanism assembly:
MCP joint	node 3	crank 3-4	node 4	2	**X4G** **Y4G**	dyad 2-4-5	3-4 (crank) 4 - 2 -5 (dyad)
	nodes 2 and 4	dyad 2-4-5	node 5		X5b Y5b PHIb2gb **X5G** **Y5G**		
	nodes 2 and 5	offset to 2-5	node 6	3	X6b Y6b PHIb3gb **X6G** **Y6G**		6 (offset)
	nodes 2 and 5		node 7		X7b Y7b **X7G** **Y7G**	dyad 4-7-8	7 (offset)
MCP & PIP joints	nodes 4 and 7	dyad 4-7-8	node 8	4	X8b Y8b PHIb4gb **X8G** **Y8G**	offset to 48	4-7-8 (dyad)
	nodes 4 and 8	offset to 4-8	node 9		X9b Y9b **X9G** **Y9G**	dyad 6-9-10	9 (offset)
	nodes 6 and 9	dyad 6-9-10	node 10	5	X10b Y10b PHIb5gb **X10G** **Y10G**		6-9-10 (dyad)
	nodes 6 and 10	offset to 6-10	node 11	6	X11b Y11b **X11G** **Y11G**		11 (offset)
	nodes 6 and 10		node 12		X12b Y12b PHIb6gb **X12G** **Y12G**	dyad 12-9-13	12 (offset)
MCP, PIP & DIP joints	node 9	crank 9-13	node 13	7	X13b Y13b PHIb7gb **X13G** **Y13G**	dyad 11-13-15	9-13 (crank)
	nodes 11 and 13	dyad 11-13-15	node 15		X15b Y15b **X15G** **Y15G**		11-13-15 (dyad)
	nodes 11 and 15	offset to 11-15	node 16		X16b Y16b PHIb7gb **X16G** **Y16G**	offset to 11-15	16 (offset)
	nodes 13 and 15	offset to 13-15	node 17		X17b Y17b PHIb7gb **X17G** **Y17G**	offset to 13-15	17 (offset)

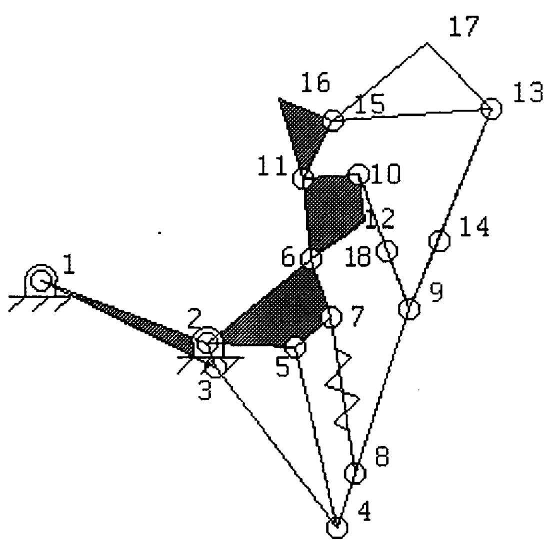
Mechanism construction for a two degree of freedom linkage (refers to figure 5.22 - FINGER6.MDX)

table 5.9

5.5.3 Construction details of the two degree of freedom linkage used for patient tests

The first stage of the clinical test programme (undertaken in Berlin) had demonstrated the necessity for developing the finger linkage and the clinical tests were temporarily interrupted whilst the design of the linkage was pursued. However, it had been shown that a single degree of freedom linkage, which could move all three finger joints simultaneously through their full range of movement, could not be developed satisfactorily before the clinical tests were resumed. Indeed, there was little confidence that a single d.o.f. linkage was technically possible. Instead, the two d.o.f. linkage was developed from its design concept to a usable orthosis and this was used for the remaining clinical test programme, undertaken with the single actuator machine (see section 5.6).

Tests with the DE/Mec software had shown that the kinematic behaviour of the linkage was very sensitive to the position of node *n*8, a matter which is discussed in the improvements to the linkage (section 7.4). In order to compensate for this sensitivity, the linkage was modified by placing a spring between nodes *n*7 and *n*8 (figure 5.24). DE/Mec model *finger7.mdx* was



Model of definitive linkage used for patient tests
figure 5.24

constructed to demonstrate the modification. The spring would typically compress three millimetres in a full cycle of the linkage when applied to patients.

The lengths of the links are listed in tables 5.10 and 5.11;

$n1n3$	$n3n4$	$n4n5$	$n4n8$	$n7n8$	$n8n9$	$n9n10$	$n9n13$	$n13n15$
68	70	65	20	55/58	60	50	75	55

Lengths of links for linkage used in patient tests
table 5.10

DIP joint locking link			*Attachment rod*	
$n14n18$	$n9n18$	$n9n14$	$n13n17$	$n15n17$
18	25	25	32	42.5

Lengths of links for linkage used in patient tests
table 5.11

The lengths of the phalanges were taken for the ring finger (see section 6.1 and table 6.12 page 180). These were;

DP ($n2$ $n6$): 24.97 mm, MP ($n6n11$) 33.84 mm, PP($n11n16$) 52.79 mm.

The kinematic behaviour of the linkage was predicted through modelling techniques (see section 5.5.4), though it was decided to design the linkage so that commercial electro-mechanical goniometers could be incorporated to provide a feature for future research. The goniometers which were used were supplied by Penny and Giles Ltd.

The linkage was designed and constructed in 'meccano' form to provide maximum flexibility in its assembly. Each link had multiple holes which could be used to alter the lengths of the links. For practical considerations in accommodating the size of the goniometers, the distances between pivots $n5$ & $n7$ and between $n10$ & $n12$ were both fixed at sixteen millimetres. Initial experience with the use of the linkage revealed that the goniometers could be easily and irretrievably damaged, especially at the vulnerable times when the linkage is either applied to, or removed from, a patient. To minimise the possibility of damage, miniature jewellery chains were inserted to provide strain relief so that the goniometers could not be over-stretched. These chains could interfere with the movement of the linkage if they were caught between the goniometer housings, so they were kept clear with elastic bands. The strain-gauged strips within the goniometers are mechanically bi-stable. Normally, they are looped above the finger joints but the metal strips could 'flip' in the opposite direction, tearing the gauge elements from their backings. The problem was particularly acute at the DIP joint so an elastic band was inserted to support the strain-gauged strip which was then mono-stable.

Mechanical 'stops' were provided to prevent accidental crushing of the strain gauged strips. Low stiffness springs were used to reduce impact forces when the linkage was allowed to move to its extreme limits of flexion and extension. These springs had no effect upon finger movement. Finally, a lightweight plastic chain was inserted between the links on the DIP joint to provide stiffness in the plane of the finger and to prevent the distal goniometer from being 'doubled up'.

All these features added to the complexity of the linkage but proved to be essential to protect the vulnerable and easily damaged goniometers.

Figure 5.25 illustrates how the ends of the goniometers are located in the blocks strapped onto the phalanges, double stacked on the proximal and middle phalanges. The goniometer end supports, fitted at the time of manufacture by Penny and Giles Ltd, were trimmed to an overall width of 6 mm so that the width of the goniometer support blocks was only 8.5 mm. The maximum width of the linkage was 10 mm.

The physical appearance of the linkage is illustrated in figure 5.26 (for the flexed position) and figure 5.27 (for the extended position). The location of node 3 in the final construction of the linkage was in a more dorsal and distal position than that shown in the figures, in order to accommodate the length of the goniometer. In practice, this had no effect on the kinematic behaviour of the linkage because the sole purpose of the crank *n*3*n*4 is to position node 4, for which the location of node 3 is irrelevant.

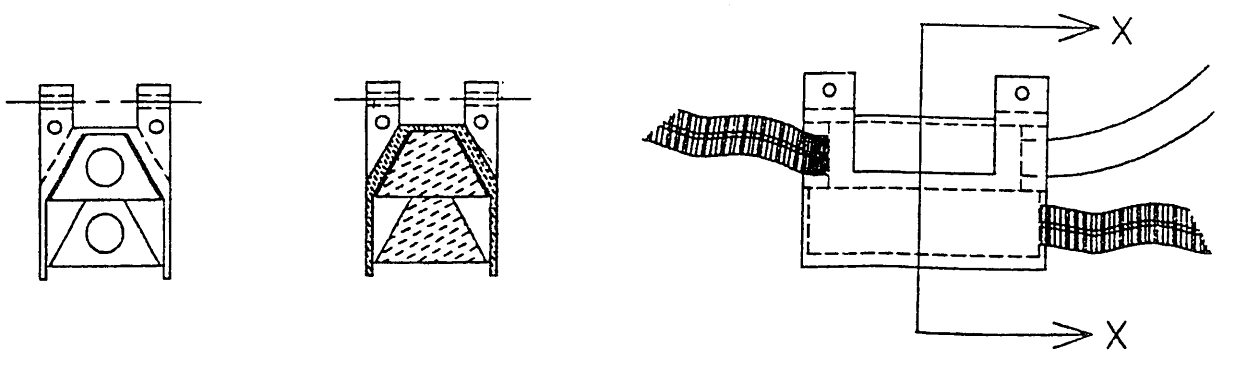
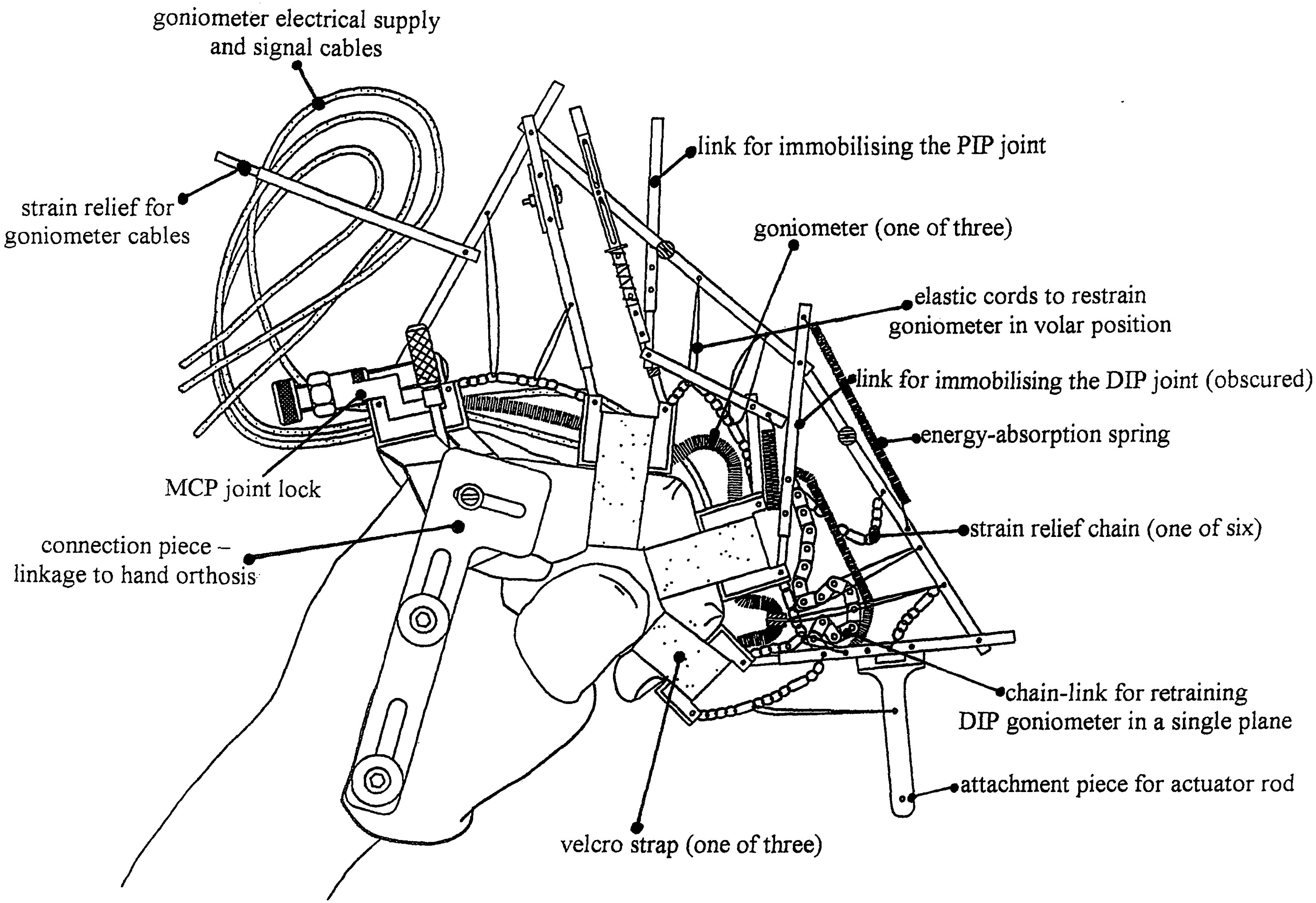
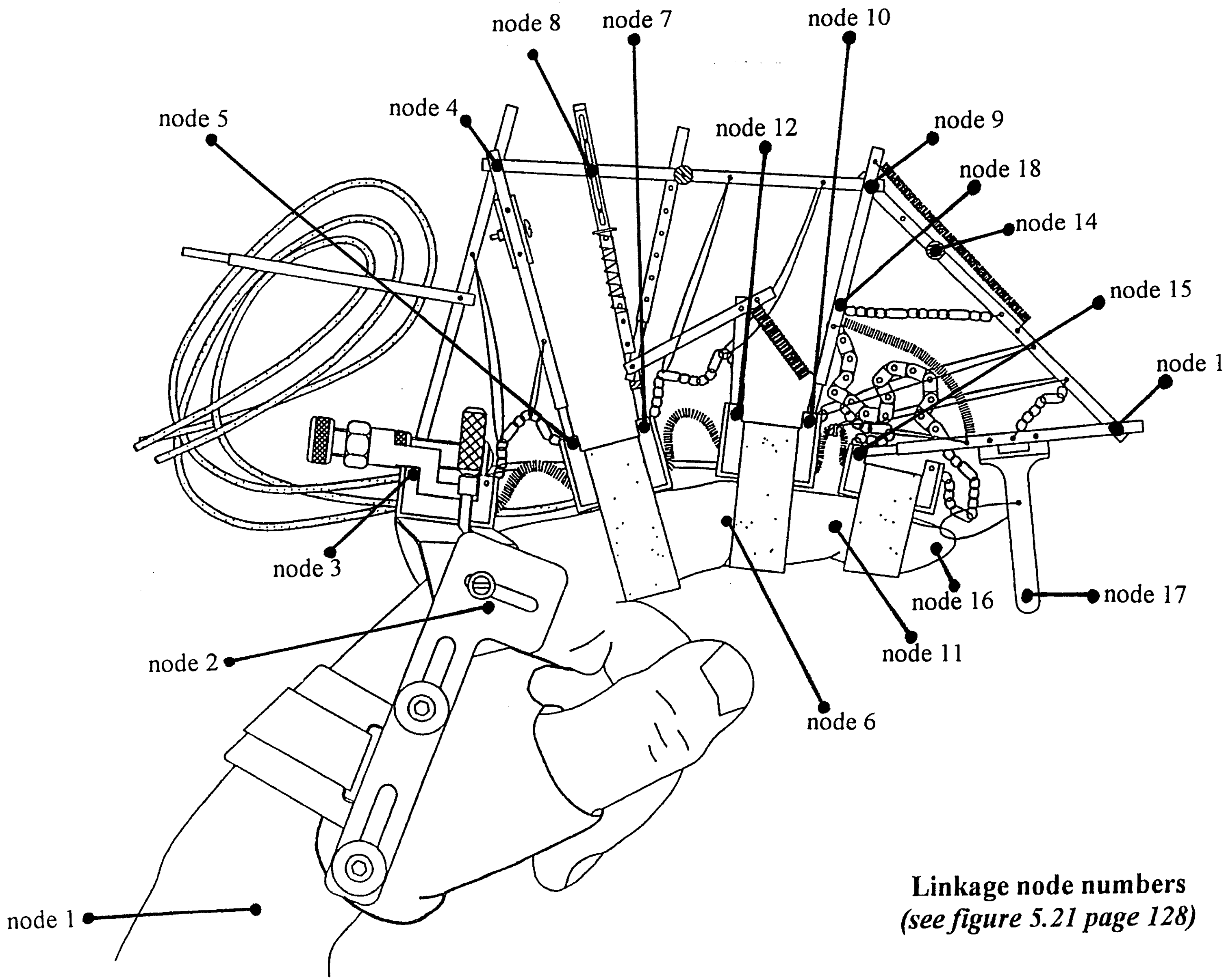


Illustration of goniometer double-stacking on the middle phalanx
figure 5.25



Linkage applied to finger in the flexed position
figure 5.26



Linkage applied to finger in the extended position
figure 5.27

5.5.4 Computer modelling of the finger linkage mechanism

Computer modelling of the linkage was performed to analyse its kinematic and kinetic behaviour. The principal aims of the modelling programs were;

- to compute the local position coordinates for the nodes in each body in a linkage
- to compute the global position coordinates for the nodes in each body in a linkage
- to determine the magnitudes of the finger joint angles
- to prepare, where appropriate, plots of the variations in joint angles for the range of crank movement

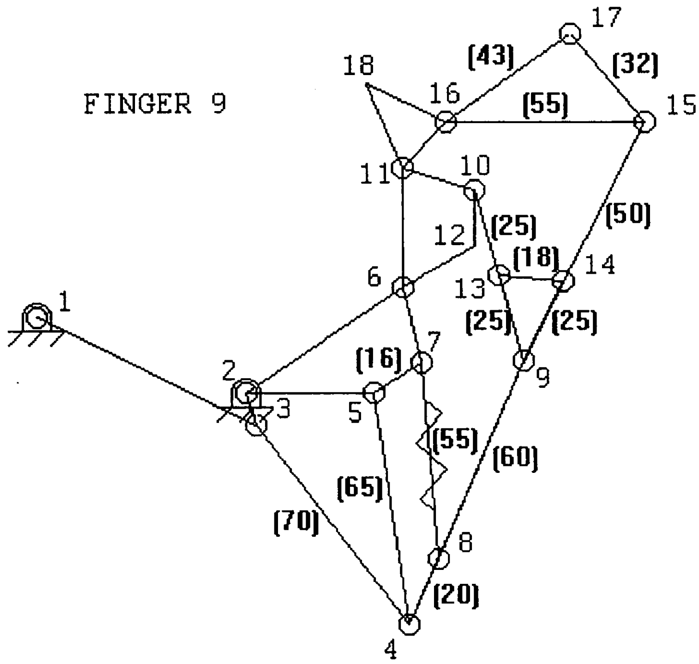
Two packages, namely DE/Mec (software for mechanism design) and Mathcad, as well as individually prepared fortran programs, were used for the modelling because each had its relative advantages and disadvantages. It was, however, a simple matter to transfer 'logic' from a mathcad to a fortran program in order to use nested loops, or to transfer the results of a fortran program to DE/Mec for checking purposes. The relative advantages and disadvantages of the programs are summarised below;

	DE/Mec advantages	**disadvantages**	**Mathcad advantages**	**disadvantages**	**Fortran advantages**	**disadvantages**
computer type		P.C. use only	'logic' rapidly developed for fortran program	P.C. use only	DEC 'alpha'	
program execution	very rapid		continuous execution for program checking		fast execution on DEC 'alpha'	batch files required
program development		difficult to 'adjust' link lengths because program always seeks full linkage assembly optimisation facilities are limited		'if' statements difficult to compile difficult to provide multiple nested loops	suitable for nested loops for purposely developed tasks	'logic' mistakes can be difficult to identify in complicated programs
graphical facilities	immediate display of kinematic behaviour		immediate display of results			secondary programs needed

Relative advantages & disadvantages of software programs for modelling the finger linkage
table 5.12

5.5.4.1 Analysis of the functional behaviour of the finger linkage mechanism

The linkage used for patient tests with the single actuator CPM machine, previously illustrated in figure 5.23, was modelled in DE/Mec as *finger9.mdx* (figure 5.28 below) but this model could not be easily modified to test the effect of fitting the linkage to fingers of *different* sizes. This was a major consideration because it was intended that the linkage should be fitted to *any* adult sized hand. The effect of different finger sizes was investigated by modelling the linkage in Mathcad software as *meccano.mcd* for which a program listing is provided in appendix 3.2.



Dimensions of linkage used for patient tests
figure 5.28

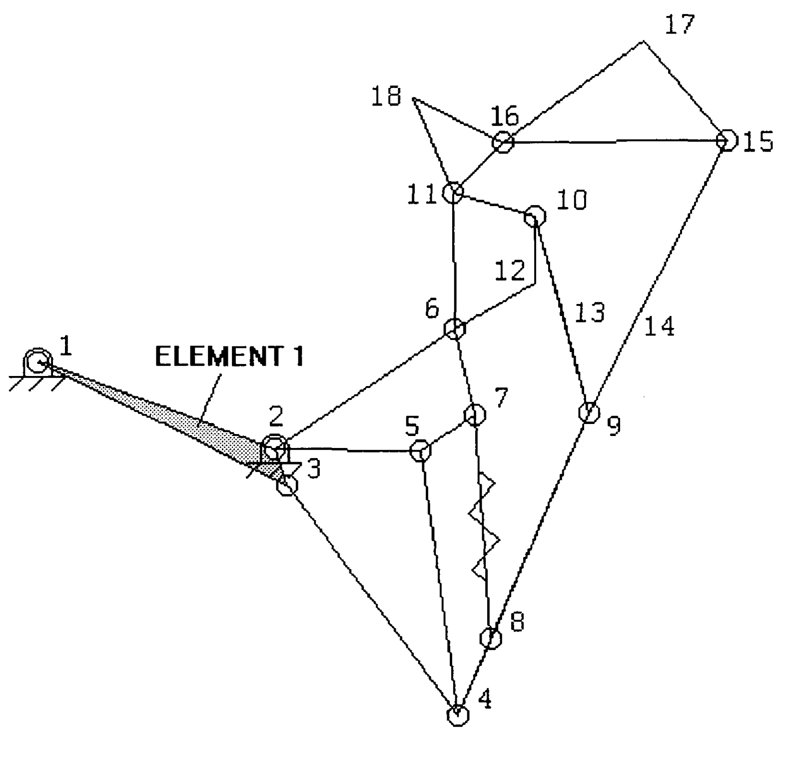
Development of the mathcad model

Mathcad program *meccano.mcd* was developed to determine the node positions of the pivots from knowledge of the geometry. The linkage was modelled as comprising seven independent elements. The angles within each element could alter as the linkage moved so the elements could not be described as rigid 'bodies'. However, the geometric relationships between the links and their internal angles in any element could be uniquely determined so the local coordinates of any node within an element could be calculated. Once the local coordinates are known and the rotation of the axes fixed to an element were calculated, the global coordinates of each node could be found by using standard vector transformation routines. The elements and their local axes systems are illustrated in figure 5.29.

The following assumptions had to be made;

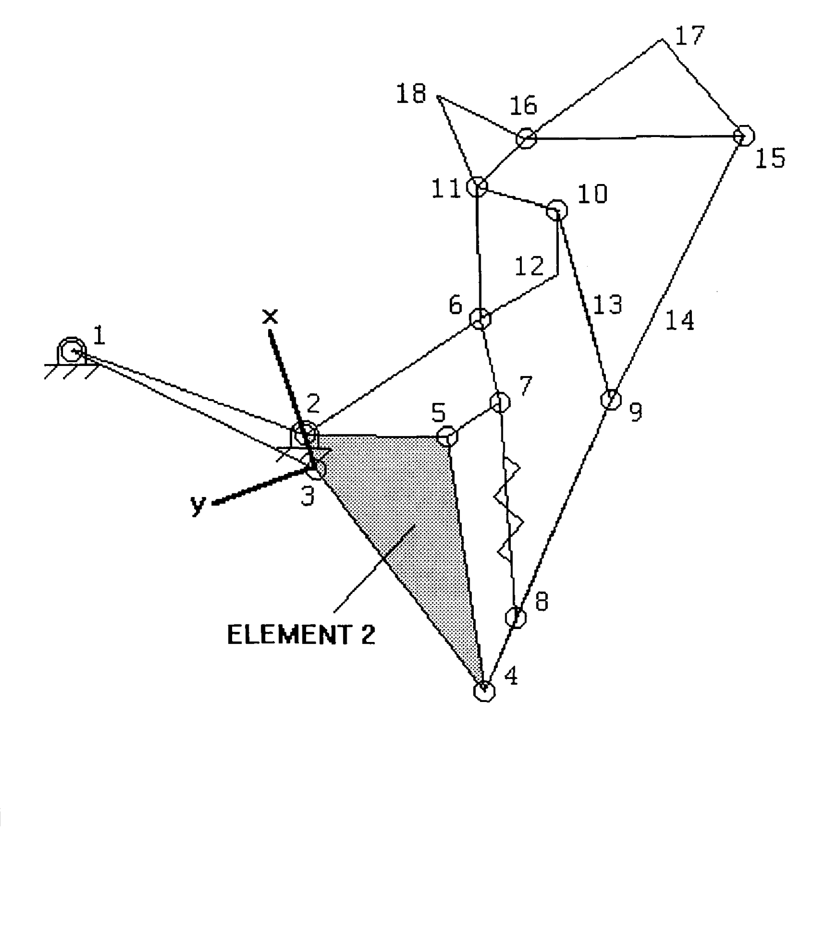
- link $n5n7$ lies parallel to the axis of the proximal phalanx $n2n6$
- link $n10n12$ lies parallel to the axis of the middle phalanx $n6n11$
- the distance between a line connecting nodes $n5$ and $n7$ and a line between nodes $n2$ and $n6$ is 20 millimetres
- the distance between a line connecting nodes $n10$ and $n12$ and a line between nodes $n6$ and $n11$ is 20 millimetres
- the distance between a line connecting nodes $n11$ & $n18$ to nodes $n15$ is 16 millimetres
- angle $n2n6n7$ is 70 degrees
- angle $n11n6n12$ is 60 degrees
- angle $n15n11n16$ is 68 degrees

Using these assumptions, which were validated by applying the linkage to patients, it was possible to calculate the coordinates of the nodes in the linkage using mathcad program *meccano.mcd* and compare them with the DE/Mec model for validation purposes. Clearly, the length of the link $n13n14$ could be varied and was typically 18 millimetres for patient tests. The effect of varying this length was also included in the analysis.



known;
ground coordinates of nodes 1, 2, 3

Local axis systems of elements in finger linkage
figure 5.29 - continued overleaf

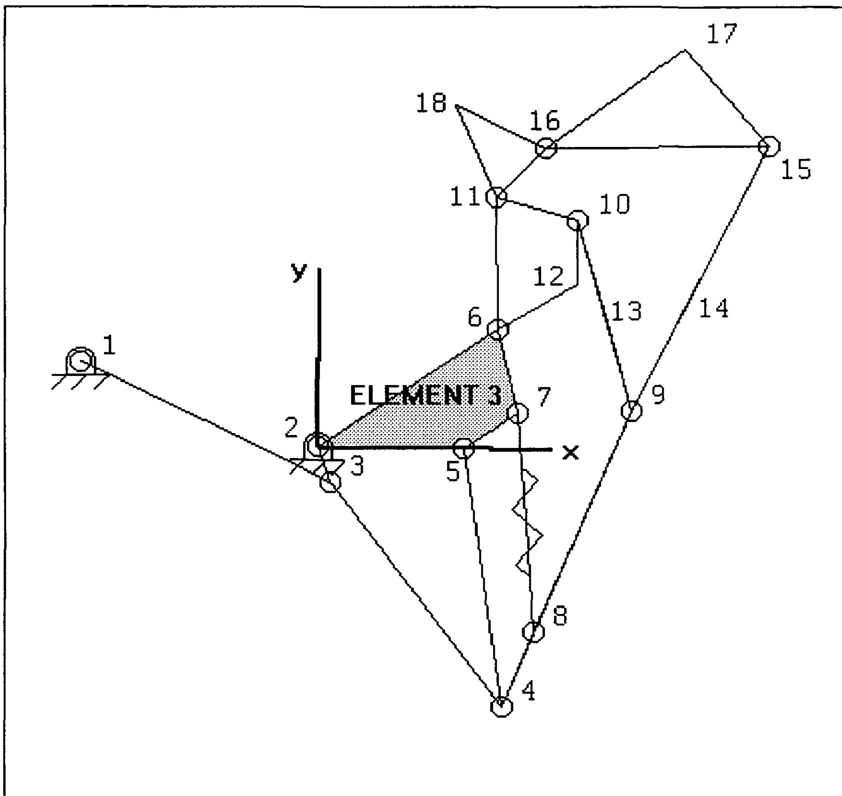


using;
the crank angle $n3n4$ w.r.t. the ground axis system,
calculate;
the crank angle w.r.t. element 2's local axis system

using;
the coordinates for nodes 2 and 4 in element 2's local axis system,
calculate;
the coordinates of node 5 in element 2's local axis system

using;
the known rotation of link $n3n4$ w.r.t. the ground,
calculate;
the ground based coordinates for node 5

now known;
nodes 1, 2, 3, 4, 5



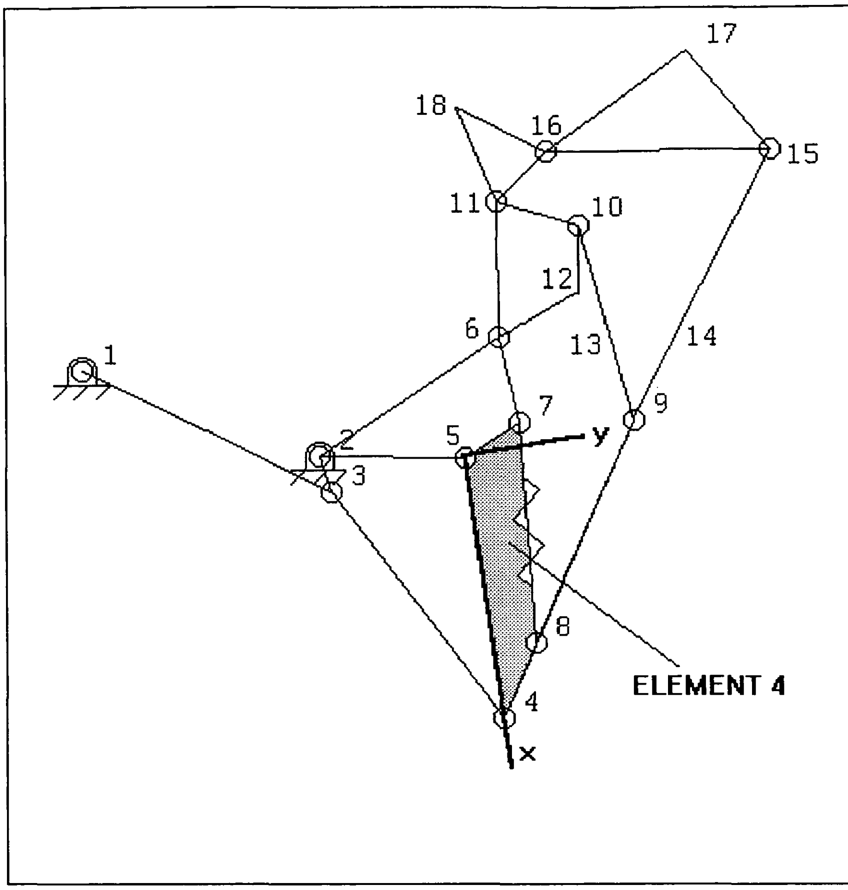
using;
known lengths in element 3
calculate;
angles 6-2-2-5 and 2-5-5-7

using;
angles 6-2-2-5 and 2-5-5-7
calculate;
the coordinates of nodes 6 and 7 in element 3's local axis system

using;
the known rotation of link $n2n5$ w.r.t. the ground,
calculate;
the ground based coordinates for nodes 6 and 7

now known;
nodes 1, 2, 3, 4, 5, 6, 7

Local axis systems of elements in finger linkage
figure 5.29 - continued overleaf

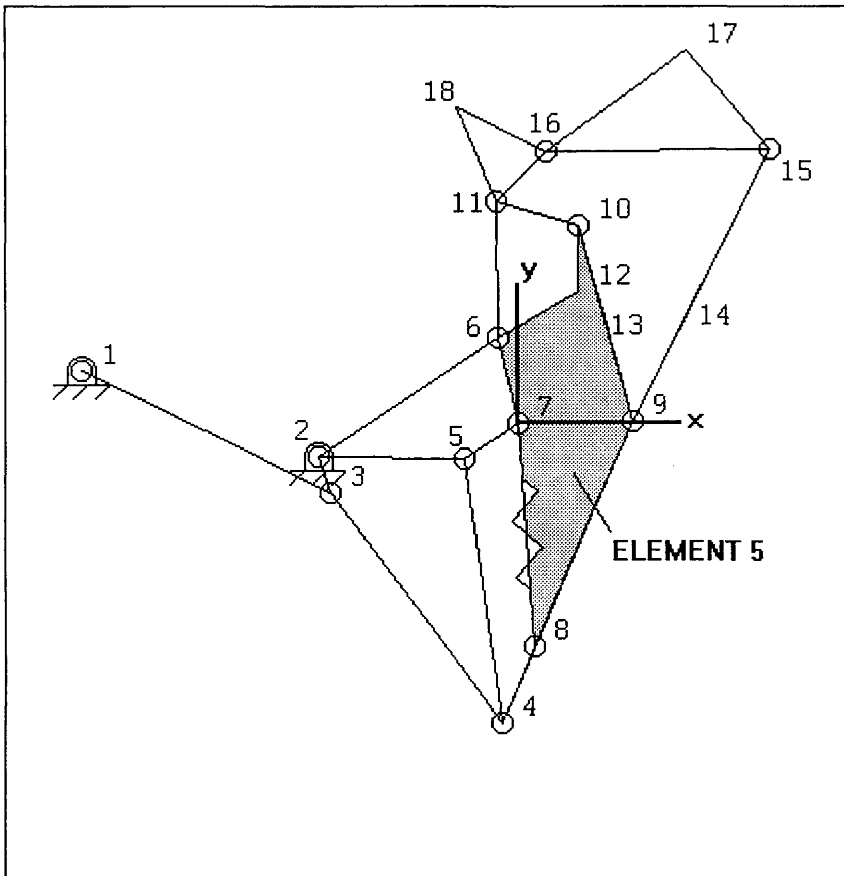


using;
known lengths in element 4
calculate;
angles 7-5-5-4, 4-8-8-7, 7-4-4-8, 5-4-4-7, 5-4-4-8

using;
angle 5-4-4-8 and length $n4n5$
calculate;
the coordinates of nodes 8 and 9 (extension of link $n4n8$) in element 4's local axis system

using;
the known rotation of link $n5n4$ w.r.t. the ground,
calculate;
the ground based coordinates for nodes 8 and 9

now known;
nodes 1, 2, 3, 4, 5, 6, 7, 8, 9



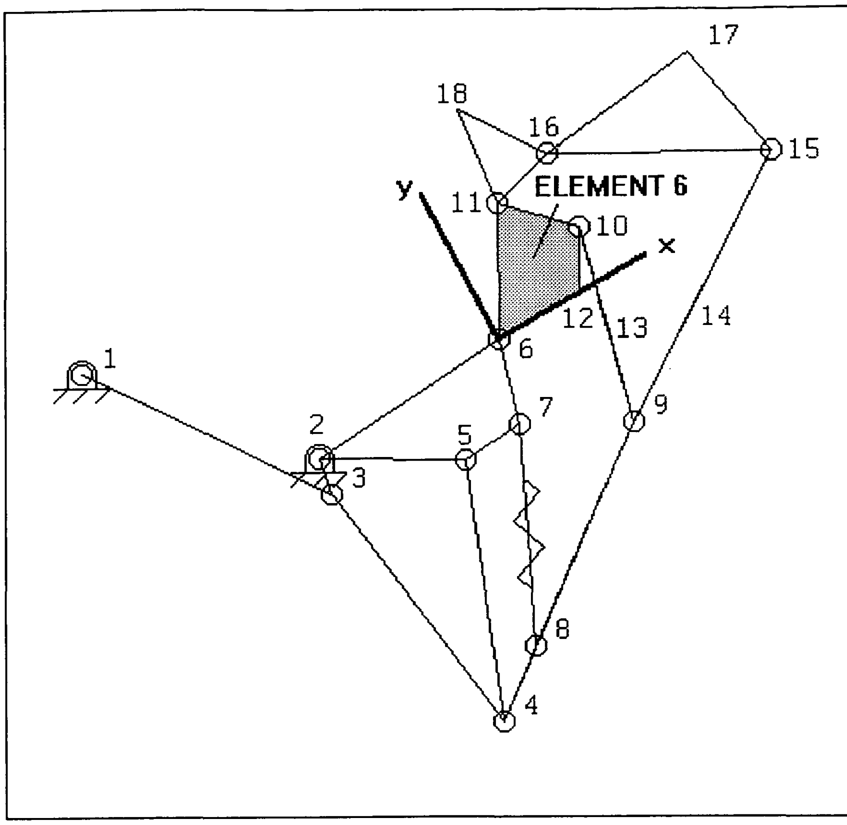
using;
lengths 7-8, 8-9, 6-7 and 7-8
calculate;
angle 7-8-8-9 and length 7-9, angle 6-7-7-9 and length 6-9

using;
angles 6-12-12-10, 7-9-9-6 and 6-9-9-10
calculate;
length 6-10 and angle 7-9-9-10

using;
the known rotation of element 5 w.r.t. the ground,
calculate;
the ground based coordinates for node 10

now known;
nodes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

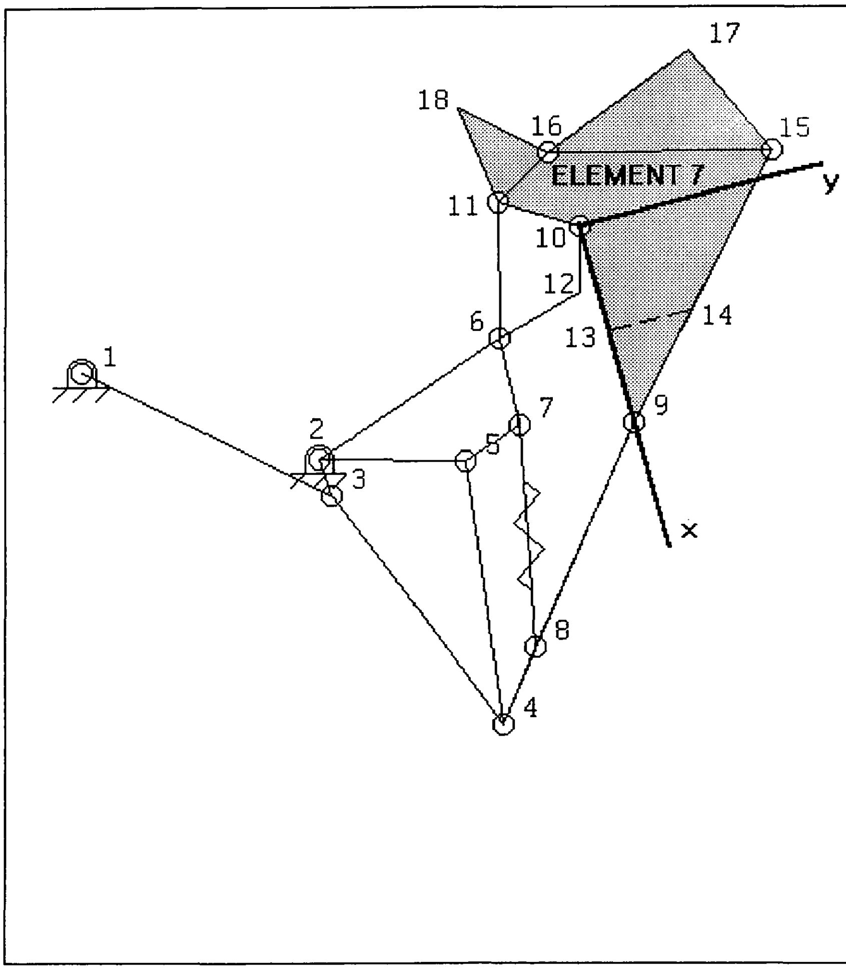
Local axis systems of elements in finger linkage
figure 5.29 - continued overleaf



using;
lengths 6-11, 6-10 and 10-11
calculate;
angle 11-6-6-10

using;
angle 11-6-6-10 and length 6-11
calculate;
element 6 based coordinates of node 11

using;
the known rotation of element 6 w.r.t. the ground,
calculate;
the ground based coordinates for node 11 and 12
now known;
nodes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12



using;
lengths 9-10, 9-13, 10-13, 9-10, 9-11, 10-13, 11-13, 10-11, 13-15, 11-15
calculate;
angles 9-10-10-13, 9-10-10-14, 9-10-10-15, 9-10-10-16, 9-10-10-17

using;
angles 9-10-10-13, 9-10-10-14, 9-10-10-15, 9-10-10-16, 9-10-10-17
calculate;
local coordinates of nodes 13, 14, 15, 16 and 17

using;
the known rotation of link 10-9 w.r.t the ground,
calculate;
the ground based coordinates for nodes 13, 14, 15, 16 and 17

now known;
all nodes

Local axis systems of elements in finger linkage
figure 5.29

5.5.4.2 *Analysis results - kinematic behaviour of the linkage in single d.o.f. configuration*

The model was used to analyse the changes in the ranges of finger joint movement, caused by;

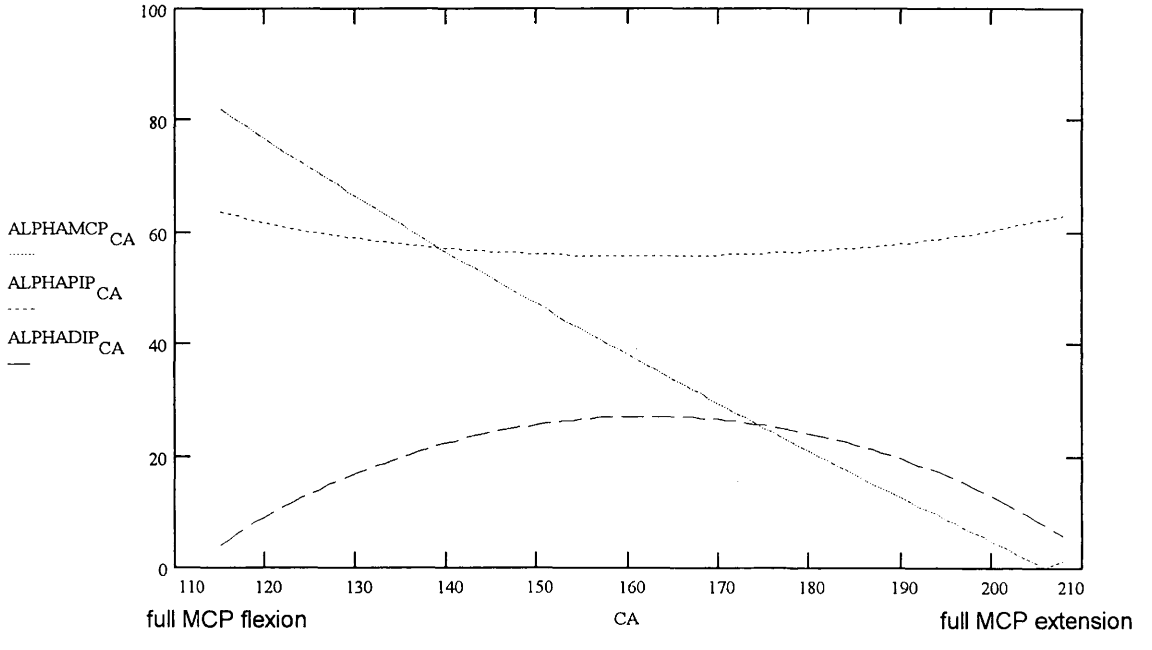
- altering the length of the locking link *n*13*n*14 (for 14 and 18 mms), using the example of the linkage applied to the ring finger;
- applying the linkage to different fingers (index, middle, ring and little) to investigate the effect of different finger sizes - for this study, the length *n*7*n*8 was set to 55 mms and the length *n*13*n*14 was set to 18 mms;

  altering the length of the link *n*7*n*8 to 60, 55, 54.7, 54.6 and 54.3 mms, when the linkage is applied to the ring finger, to investigate the effect of altering the spring length.

Effect of altering the length of the inter-locking link n13n14

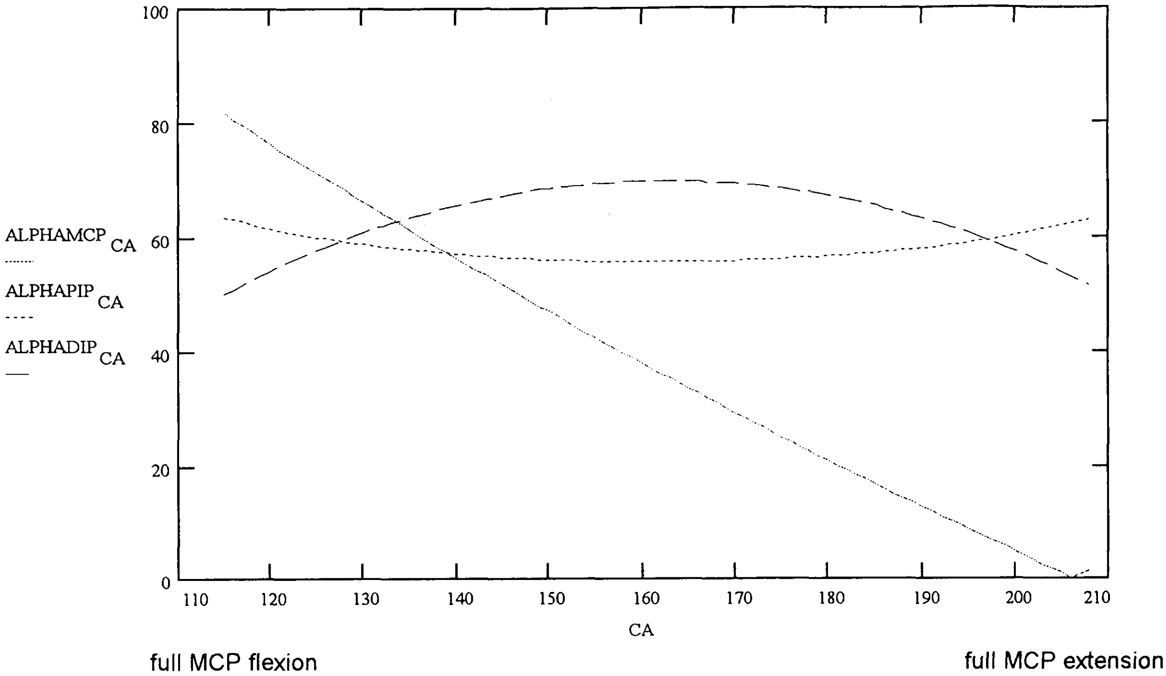
The effect of altering the length of this inter-locking link upon the range of finger joint motion is illustrated below, for the linkage applied to the ring finger.

(a) Case 1: length of n13n14 = 18 mms



Changes in finger joint angles for a cycle of motion - inter-locking link of length 18 mm
figure 5.30

(b) Case 2: length of n13n14 = 14 mms



Changes in finger joint angles for a cycle of motion - inter-locking link of length 14 mm
figure 5.31

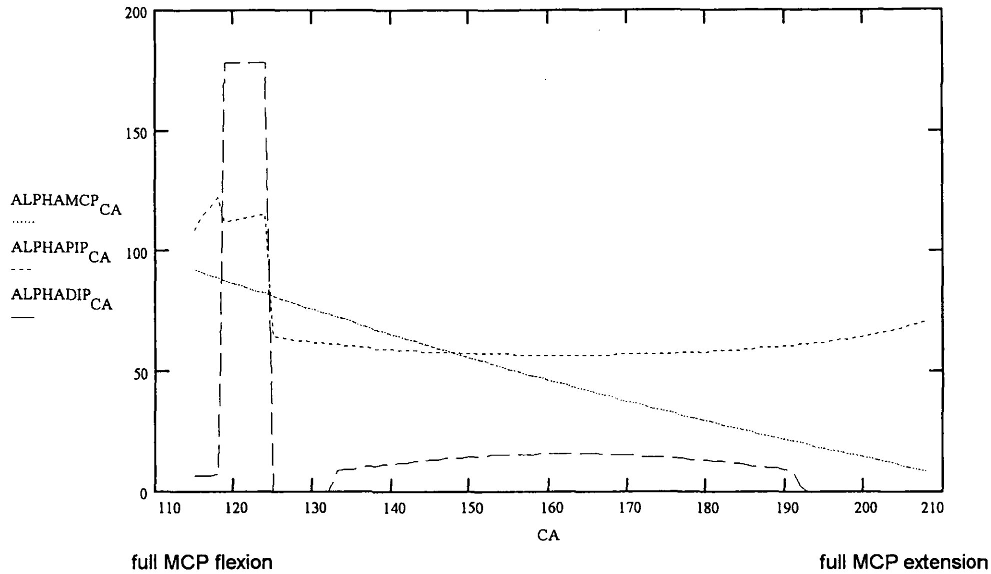
Conclusion

Altering the length of the link $n13n14$ changes the range of movement of DIP joint from 4^0 to 27^0 (for a link length of 18 mms) to 4^0 to 27^0 (for a link length of 18 mms), for the full cycle of MCP joint movement. This means that the linkage could be fitted to fingers with different limitations in DIP joint range of motion.

Effect of applying the linkage to different fingers (index, middle, ring and little)

The effect of applying the linkage to different fingers, with the inter-connecting link $n13n14$ set to 18 mms, is illustrated below.

(a) Case 1: linkage applied to the little finger

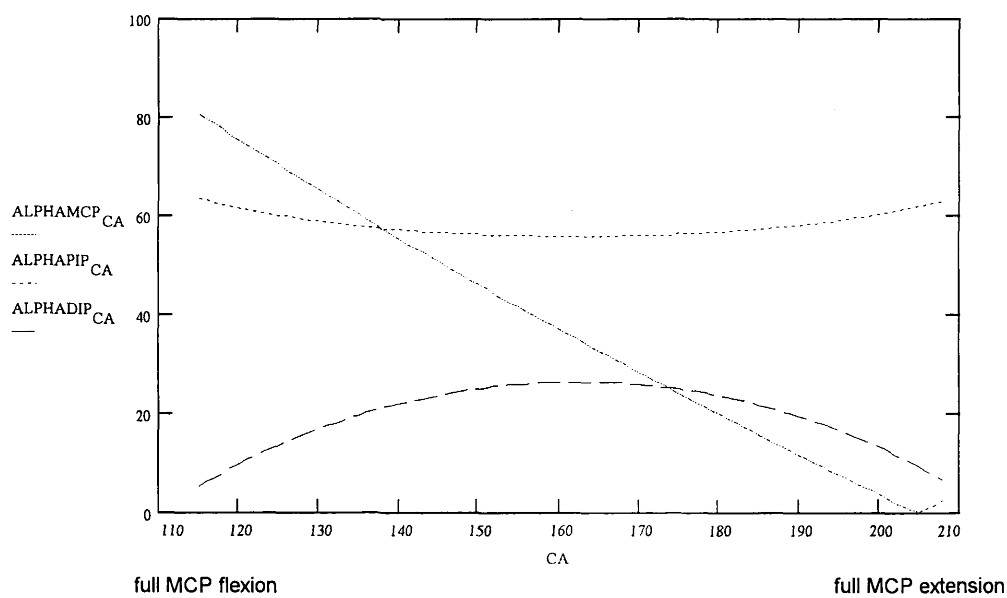


Changes in finger joint angles for a cycle of motion linkage applied to little finger
figure 5.32

(b) Case 2: linkage applied to the ring finger

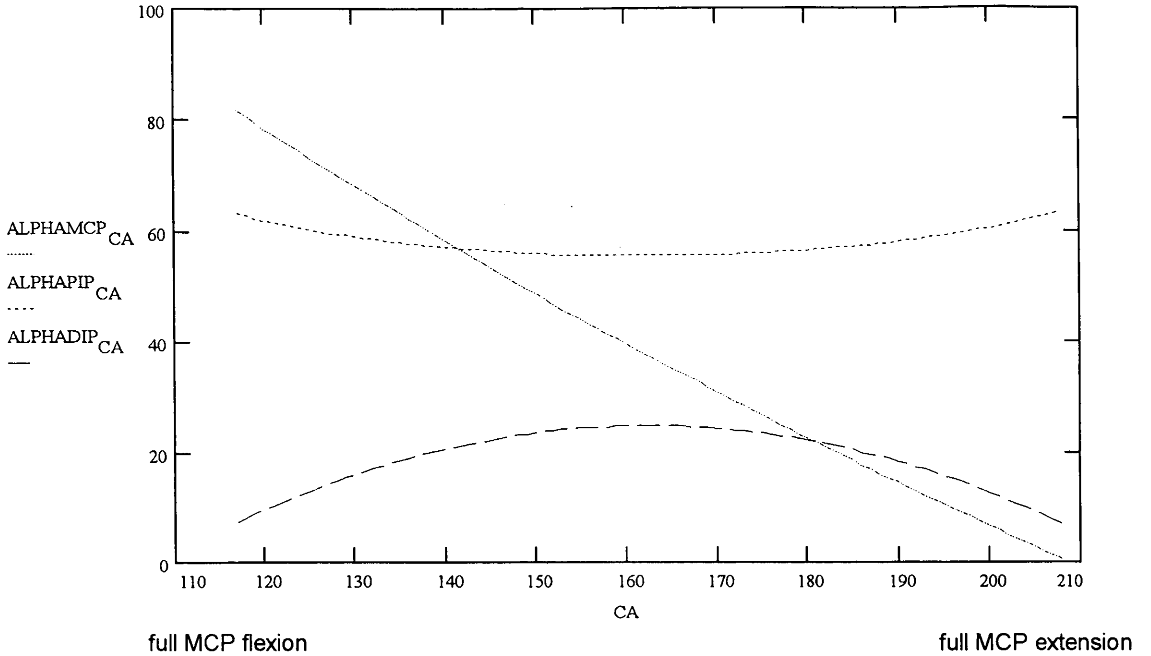
This was previously illustrated in figure 5.30.

(c) Case 3: linkage applied to the middle finger



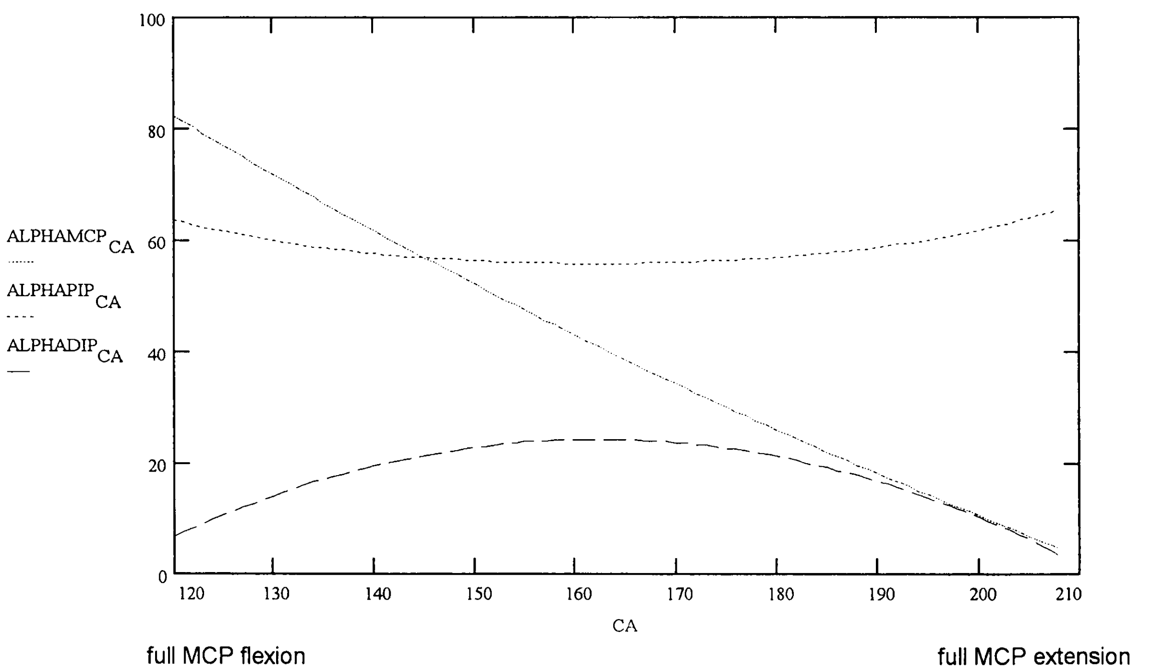
Changes in finger joint angles for a cycle of motion linkage applied to middle finger
figure 5.33

(d) Case 4: linkage applied to the index finger



Changes in finger joint angles for a cycle of motion linkage applied to index finger
figure 5.34

(e) Case 5: linkage applied to the Nordin & Frankel normative model of a finger



Changes in finger joint angles for a cycle of motion linkage applied to Nordin & Frankel normative model of a finger
figure 5.35

Conclusion

The method adopted for determining the effective lengths of the phalanges for each finger is described in section 6.1, and these lengths are shown in the first three columns of table 5.13 below. These values were used as variable parameters in the finger & linkage model and it was found that the joints' ranges of motion (R.O.M.) were highly comparable for all four fingers. The exception was the little finger, for which the linkage 'collapsed' when the MCP joint was 80^0, but this was considered an extreme case. The data for phalangeal lengths published by Nordin and Frankel produced comparable data. The results of the model analysis are listed in table 5.13. It was concluded that a highly satisfactory modelling result had been obtained and the linkage would be suitable for the four fingers inspite of their different sizes.

	phalangeal lengths (millimetres)			joint range of motion (degrees)		
	distal phalanx	*middle phalanx*	*proximal phalanx*	*DIP r.o.m.*	*PIP r.o.m.*	*MCP r.o.m.*
index finger	22.52	27.76	50.39	7 - 24	55 - 63	0 - 82
middle finger	23.88	32.50	54.25	5 - 26	55 - 63	0 - 82
ring finger	24.97	33.84	52.79	4 - 27	55 - 64	0 - 82
little finger	21.23	22.87	42.04	4 - 16	56 - 64	0 - 80
Nordin & Frankel	18	28	46	7 - 24	55 - 64	0 - 82

Summary of ranges of motion obtained with linkage applied to different fingers
table 5.13

The need to introduce a spring in link *n7n8*, because of the sensitivity of the position of *n8* on the kinematic behaviour of the linkage, was described in section 5.5.3. It was necessary to analyse the effect of altering the length of the spring upon the range of motion of the PIP joint, using *meccano.mcd* (appendix 3.2). The analysis revealed that the range of motion at the PIP joint is limited if the link does not change length (i.e. the link is rigid and no spring is inserted), but that 63^0 of movement is possible if the link length changes from 54.7 to 62 mms. The results are shown in table 5.14 below.

link length *n7n8* (mms)	**PIP R.O.M. (degrees)**
fixed length:	
62	3 - 7
60	12 - 14
55	56 - 62
54.7	59 - 66
variable length:	
62 - 54.7	3 - 66

Effect of altering the length of link n7n8 upon PIP range of motion
table 5.14

5.6 Design, manufacture and functional tests upon the single actuator CPM machine

5.6.1. Introduction

Within the chronological series of activities, the Berlin clinical trials proceeded at the same time as the development of the linkage. Once the linkage was completed, it was decided to evaluate it in Dundee and another actuator had to be fabricated for this purpose. This section describes the second machine.

The need to make another actuator provided an opportunity to revise design features in the first machine that had been shown to be deficient in some manner. The principal problems had been unacceptable wear in the guide for the transducer support and in the gearhead bearings. These matters were addressed in the second machine. In addition, the opportunity was taken to incorporate more sensitive load measurement features (transducer and selectable gains for amplifiers). The machine was constructed so that it could be supported on a universal joint attached to a chair. Patients could be seated comfortably during tests and the fingers moved in their proper plane of motion. Like its predecessor, the second CPM machine had feedback position control and selectable range & rate of finger joint motion.

A limited number of tests had been performed in Berlin to use the CPM machine for static stretching of contracted finger joints. Clinicians and therapists had been curious to discover whether static stretching would have the same effect on finger joint range of movement (ROM) as cyclic movement. They performed a limited number of tests to measure both changes in ROM and changes in the magnitude of force necessary to extend a contracted finger joint at the limit of its range of movement. It was found that the magnitude of exerted force did decrease with passive static stretching but patients would feel discomfort. These tests were outside the remit of the research programme and were not pursued. Nevertheless, it was agreed that the facility to pause the machine's motion at the limits of its movement should be incorporated as a useful feature for future research.

5.6.2 Transducer carriage assembly (TCA)

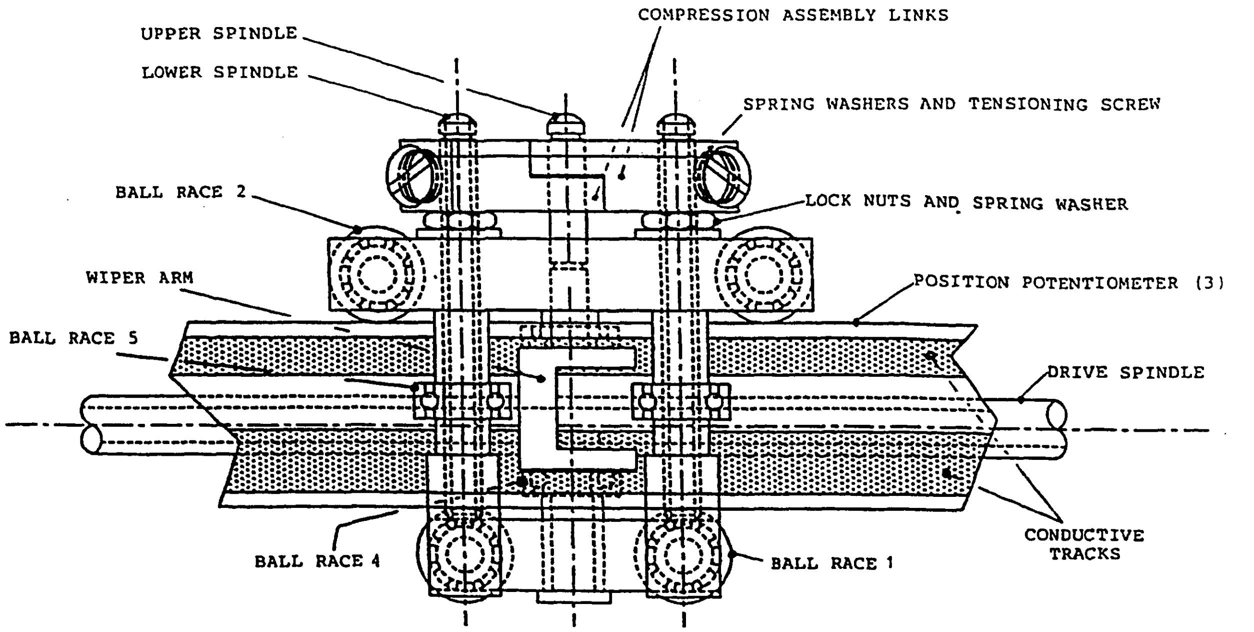
The central component of the actuator was a transducer carriage assembly (TCA) illustrated in figures 5.36, 5.37 and 5.38. Its primary purpose was to rigidly support the force transducer with respect to the potentiometer, in such a way that the transducer had a single degree of freedom with respect to the potentiometer. Its other purposes were to sense the transducer's position with respect to the frame of the machine, to avoid inadvertent electrical shorting of the conductive plastic potentiometer, and to minimise mechanical wear, the level of noise emitted from the machine and the need for lubricants.

A major consideration in the design of the TCA was the necessity for minimal mechanical wear, a problem which had been experienced with the first twin-actuator machine. If it were assumed that a machine is required to provide an average stroke length of seventy millimetres, the time for a complete cycle is twenty seconds, it is used five hours per day, it operates five days in each week and forty five weeks each year, then the total distance moved by the actuator in one year would be 28 km! This presented a considerable design challenge and the use of the ball bearings in the assembly ensured that the moving parts between the potentiometer and the force transducer were subjected to rolling friction, not sliding friction, thereby minimising wear.

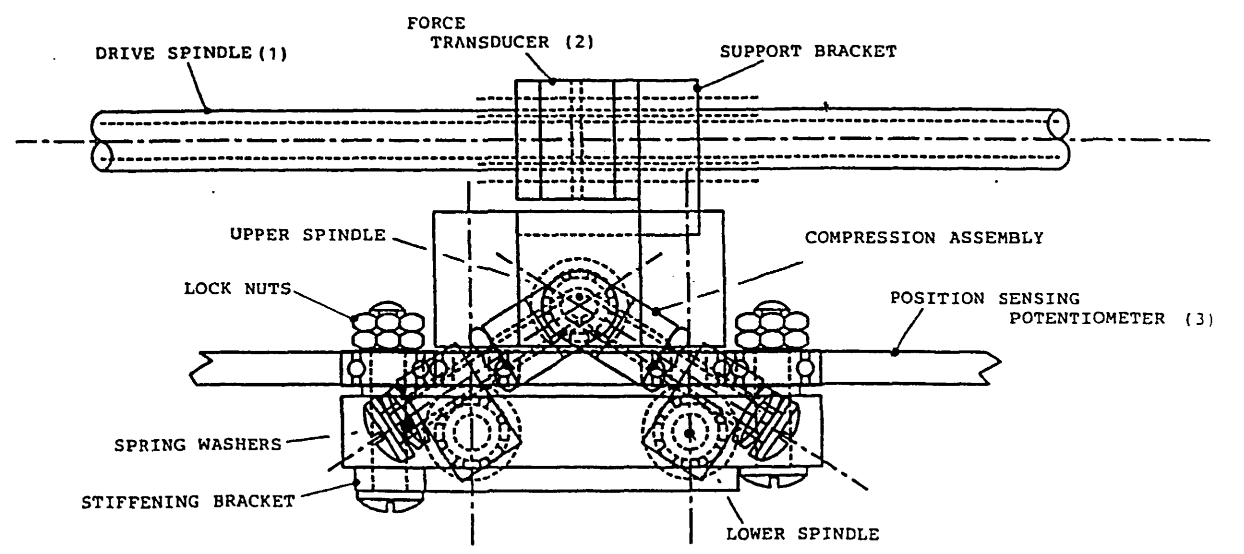
The other interface in the assembly, which was subjected to wear, was the nylon lead screw in the aluminium alloy transducer. A continuous three month endurance test performed on a duplicate machine revealed that the wear rate of the aluminium alloy would be unacceptable if the machine were used for extended periods of time but could be tolerated for the limited duration of the tests required for the research programme. It was found that a steel-nylon interface was acceptable and this was provided in the third prototype CPM machine.

Figures 5.36, 5.37 and 5.38 show underside, side and end views of the force transducer carriage assembly respectively.

Figure 5.36 shows the underside view of the transducer carriage assembly (excluding the support bracket for purposes of clarity). The potentiometer has two conductive tracks which have an electrical connection between them, provided by the wiper arm. This wiper



Underside of the transducer carriage assembly (TCA)
figure 5.36



Side view of the transducer carriage assembly (TCA)
figure 5.37

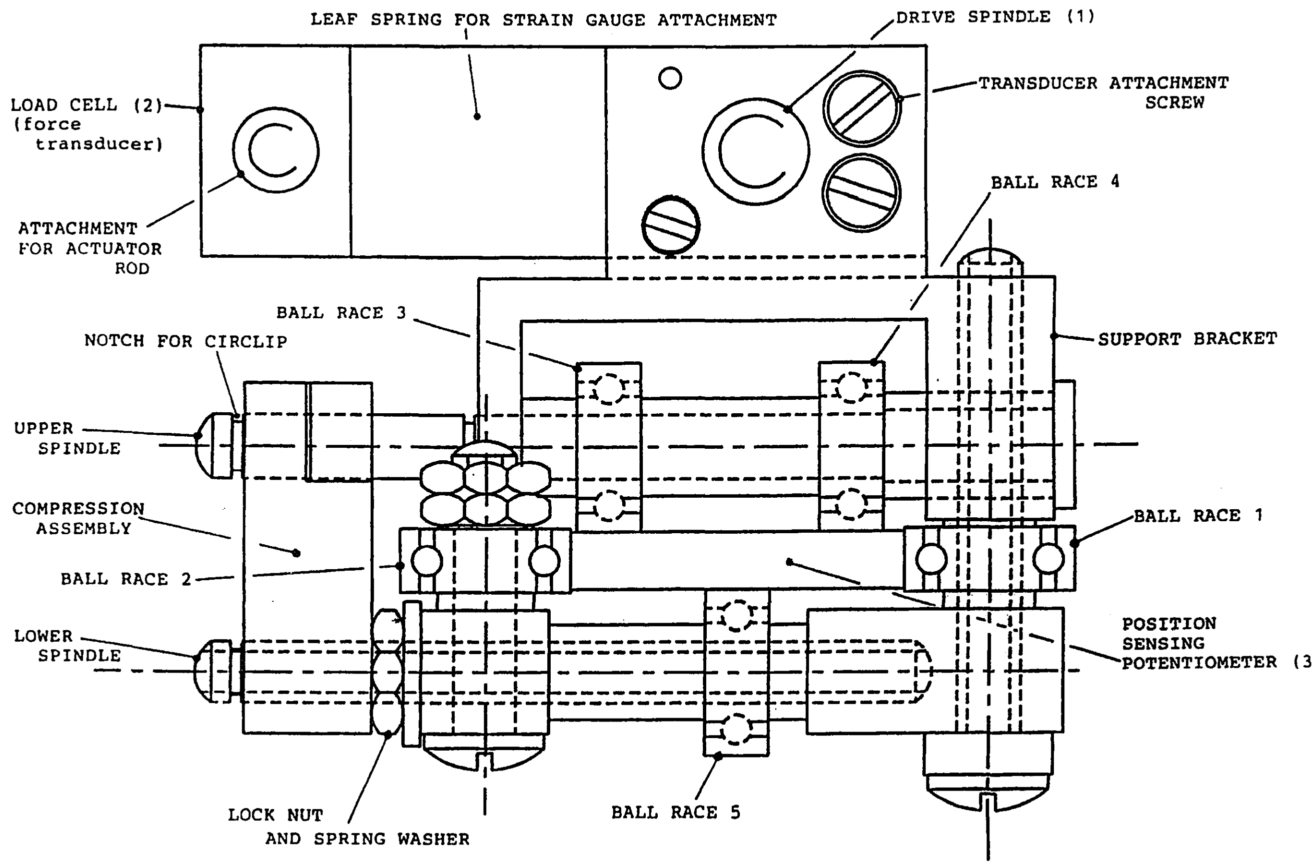


figure 5.38

End view of the transducer carriage assembly (TCA) arm is attached to the transducer carriage assembly by a simple bracket (not shown for clarity). The longitudinal axis of the drive spindle is approximately coincident with the longitudinal axis of the potentiometer. The effect of this arrangement is that there is minimal bending about a perpendicular axis passing through the centre of the potentiometer and out of the plane of the paper, when the actuator rod exerts force. This reduces component wear.

Figure 5.37 which is a side view of the TCA, illustrates the location of the compression assembly which provides a continuous compressive force on the lower surface of the potentiometer to keep it in continuous contact with the support bracket. Also shown is the location of the force transducer with respect to the support bracket and the lead screw.

Figure 5.38 illustrates how the force transducer is attached to the transducer carriage assembly by means of three transducer attachment screws and a location pin. The main support bracket of the carriage assembly is the central structure, which is located on the position sensing potentiometer. The illustration shows one of two ball race bearings, fixed to the support bracket, which butt against the right hand vertical edge of the position sensing potentiometer. The position potentiometer is compressed against these bearings by another bearing, which is in contact with the left-hand vertical edge of the potentiometer. The spring nut and washer on the lower spindle maintain the required compressive force. Wear on the outer vertical edges of the potentiometer is compensated for by expansion of the spring washer. This arrangement ensures that there is no lateral (left-to-right) movement of the support bracket with respect to the position sensing potentiometer, which in turn means that there can be no relative lateral movement of the force transducer with respect to the potentiometer. An upper spindle in the support bracket is inserted through the inner races of two bearings that are in contact with the upper surface of the position sensing potentiometer. The lower surface of the potentiometer is acted upon by another ball race bearing, located on the lower spindle. The assembly holds the potentiometer in compression between the ball races on the upper and lower spindles. This arrangement ensures that there is no vertical (up-down) movement of the support bracket with respect to the position sensing potentiometer, which in turn means that there can be no relative vertical displacement of the force transducer.

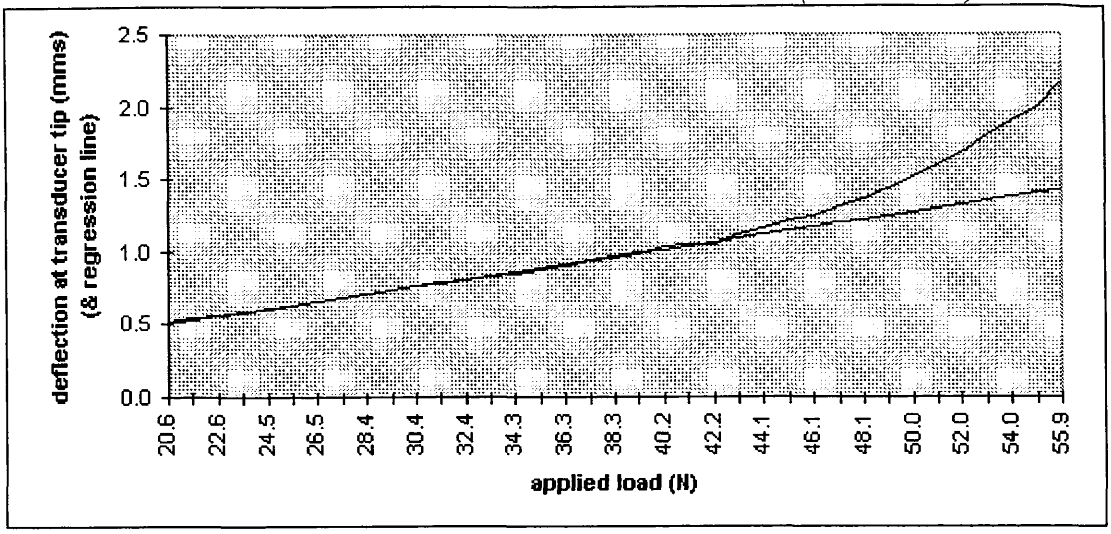
5.6.3 Transducer design and characteristics

The force transducer was rigidly secured at one end to the drive mechanism in the actuator assembly, and pivoted at the other end to support the actuator rod. The transducer carriage assembly (TCA) supported this transducer upon a conductive plastic linear potentiometer. Flexible conductive strips were used to energise the load cell and to conduct electrical signals.

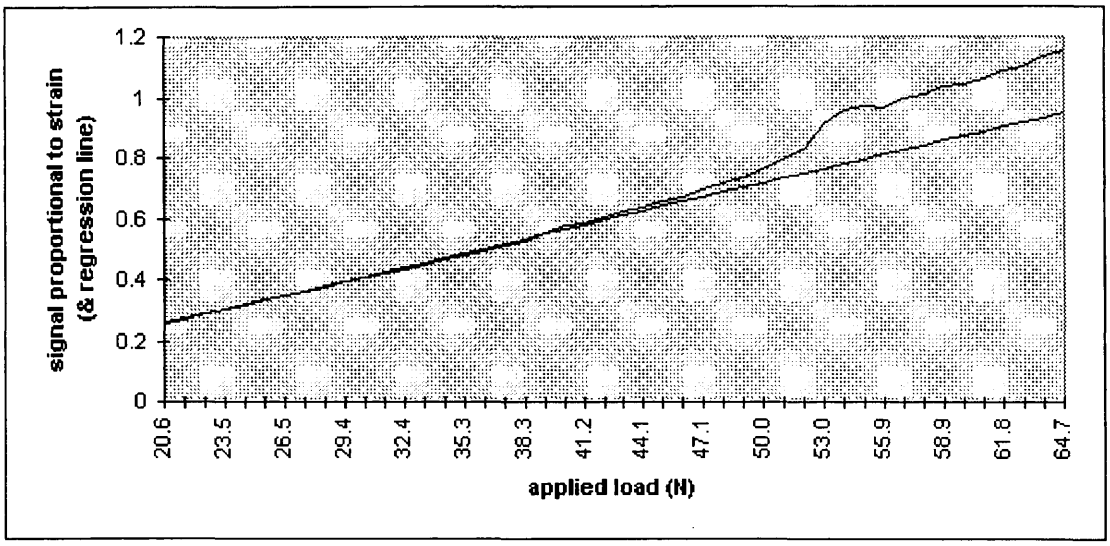
The transducer was a strain-gauged cantilever, spark-eroded from aluminium alloy type 7017 and shot-peened before gauges were applied. The gauges used were MM CEA-13-062UW-350 connected in a full bridge circuit. In view of the high magnitudes of forces that had been encountered with the first twin-actuator machine, it was decided to design the second actuator's transducer so that it could withstand an applied load of at least 30 Newtons without damage. The design of the transducer took into account the stress concentration factors associated with its contoured surface but it was decided to test a sample transducer to failure, using the same loading conditions as would be experienced in practice, rather than rely solely on proof stress data. The sample transducer beam was gauged with 'student gauges', though the signals from the gauges were not converted directly to strain magnitudes since it was only necessary to obtain signals proportional to strain. The destruction tests were performed by rigidly clamping the threaded end of the beam and loading the free end with masses. A dial test indicator was used to measure the deflection of the free end, and the strain signals recorded, as the transducer was loaded to destruction. The results of the tests are plotted in figures 5.39 for transducer tip deflection and 5.40 for signals proportional to strain, together with their linear regression plots.

The first indication of yield was difficult to determine accurately because the change in gradient from linear to non-linear for both graphs were gradual, as would be expected for a ductile material. The load versus strain graph gives the first indication of yield with a load of 40.2 N and the load versus deflection graph gives the first indication of yield with a load of 42.2 N. Based on the knowledge gained with tests with the twin actuator system, it was decided that this would provide an adequate factor of safety.

(TRANTEST.XLS)



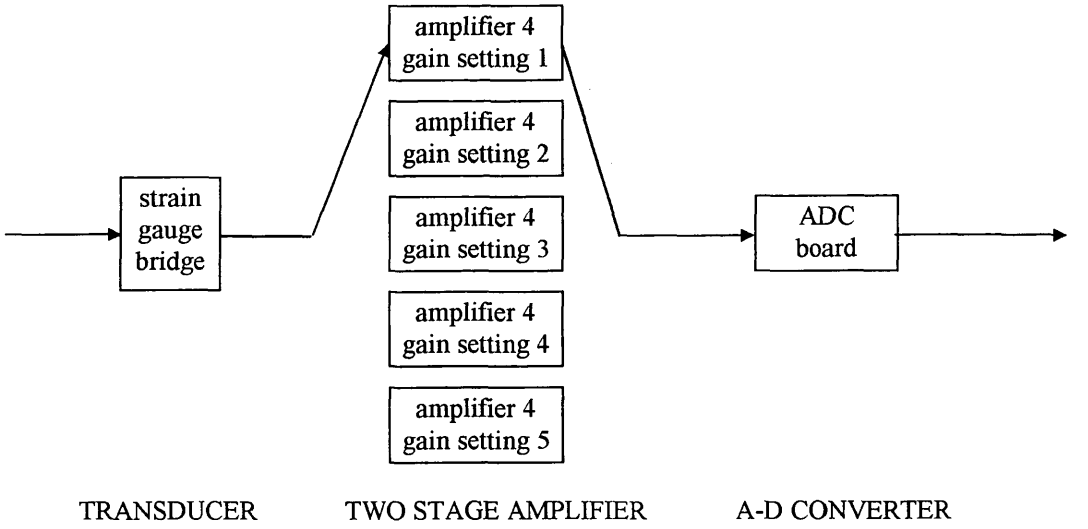
Transducer destruction test results - tip deflection and regression line versus load
figure 5.39



Transducer destruction test results - strain gauge signal and regression line versus load
figure 5.40

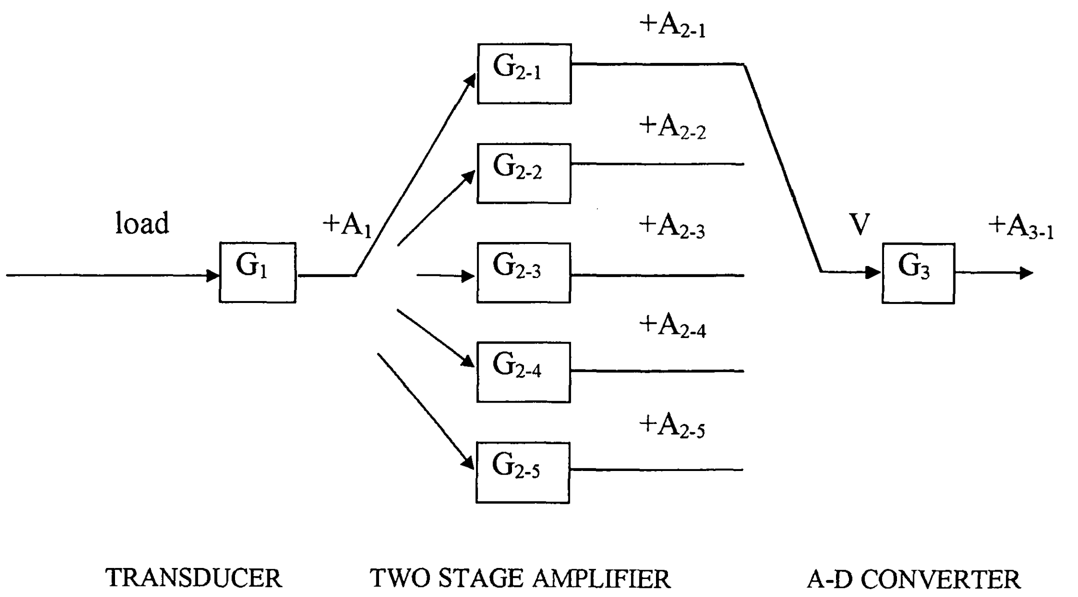
5.6.4 System performance and calibration

The transducer bridge supply was provided from a 1.2 volt reference supply, connected to a non-inverting amplifier and then to an inverting amplifier, to provide a +/- 2.25 volt bridge supply. Amplification of the transducer signals was made in two stages; the pre-amplifier had a fixed gain of 100 and the second stage amplifier was designed to provide variable gain settings. *(See note at the bottom of the next page)*. The block diagram of the system's signal flow is shown in figure 5.41 below, using amplifier number 4 gain setting 1 as the default. Note that the two amplifiers are considered as a single unit.



Block diagram of signal flow – twin actuator system
figure 5.41

Offsets were provided for the null adjustment of the transducer signal amplifier and for the analogue to digital converter. This provided a bit value of 2048 (i.e. 4096/2) for no load, a bit value of 4096 for maximum tensile load and a bit value of 0 for maximum compressive load. The nomenclature for the individual elements' transfer functions (G_{i-j}) and offsets (A_{i-j}) is illustrated below in figure 5.42.



Block diagram of elements' transfer functions and adjustment offsets – twin actuator system
figure 5.42

The units for the transfer functions are;

G_1	mV/N
$G_{2\text{-}1}$, $G_{2\text{-}2}$, $G_{2\text{-}3}$, $G_{2\text{-}4}$, $G_{2\text{-}5}$	V/mV
G_3	bits/V

The transfer of a force value to a bit value can be calculated using the expression;

	Load (N)	=	F_1
$[F_1 \times G_1$ (mV/N)]	+ A_1(mV)	=	F_2
$[F_2 \times G_{2\text{-}i}$ (V/mV)]	+ $A_{2\text{-}i}$ (V)	=	F_3
$[F_3 \times G_{3\text{-}i}$ (bits/volt)]	+ 2047 (bits)	=	F_4
	F_4	=	bit value of the applied load, L

The method used to determine the transfer functions was to apply load to the transducer in increments of 100 gm and record the following readings;

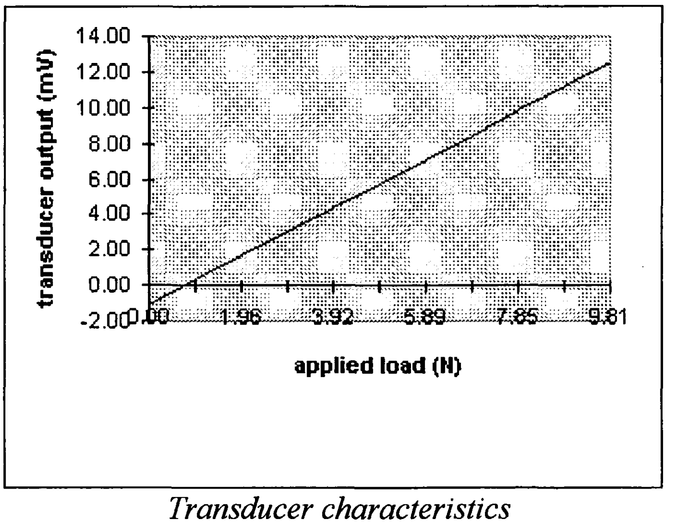
(i) millivolt output from the bridge (i.e. millivolt input to the amplifiers)

(ii) voltage output from amplifier 4 for each of the five gain settings (i.e. the voltage input to the ADC in the laptop)

(iii) the bit reading for the ADC42 analogue to digital converter

The results are shown in table 5.15 and illustrated in figures 5.43, 5.44 and 5.45 below.

Transducer



Transducer characteristics
figure 5.43

The transfer function G_1 is 1.385 (mV/N)

The offset A_1 is -1.06 mV

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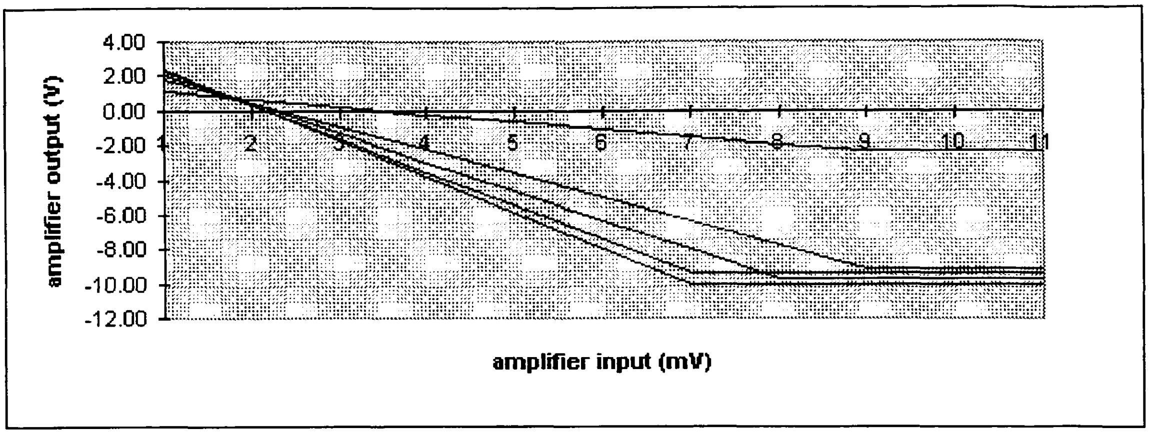
Note: The electronic circuits for the CPM system were developed by Mr Bill Legg and Mr Mike Doyle, former members of staff in the department of electronic and electrical engineering.

Amplifier

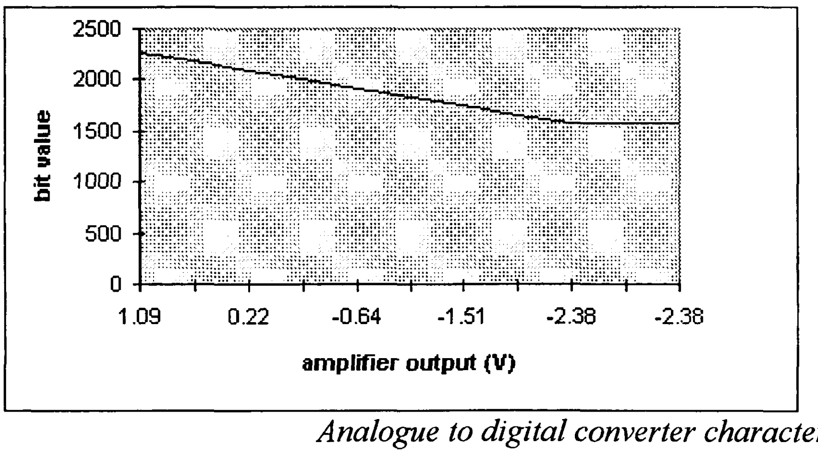


Amplifier characteristics (different gain settings)
figure 5.44

Amplifier:

setting 1	*setting 2*	*setting 3*	*setting 4*	*setting 5*
Amplifier transfer function, G_{2-1}, is -0.3188 (V/mV)	Amplifier transfer function, G_{2-2}, is -1.0023 (V/mV)	Amplifier transfer function, G_{2-3}, is -1.2315 (V/mV)	Amplifier transfer function, G_{2-4}, is -1.4225 (V/mV)	Amplifier transfer function, G_{2-5}, is -1.5273 (V/mV)
The offset, A_{2-1} is 0.75 (V)				
Saturation at; 9.85 (mV); i.e. 7.8 (N)	Saturation at; 9.85 (mV); i.e. 7.8 (N)	Saturation at; 7.07 (mV); i.e. 5.9 (N)	Saturation at; 7.07 (mV); i.e. 5.9 (N)	Saturation at; 7.07 (mV); i.e. 5.9 (N)

Analogue to Digital Converter



The analogue-to-digital converter transfer function G_3 is 200.3 (bits/V).

The example shown is for amplifier gain setting 1, with its saturation point.

The bit value for 0 volts input is 2047.

Analogue to digital converter characteristics
figure 5.45

SUMMARY OF SIGNAL FLOW FOR VARYING AMPLIFIER GAIN SETTINGS

Applied Mass x (0.1 kg)	Load (Newtons)	Amplifier Input (mV)	GAIN SETTING 1 Amplifier Output (V)	GAIN SETTING 1 Bit Value	GAIN SETTING 2 Amplifier Output (V)	GAIN SETTING 2 Bit Value	GAIN SETTING 3 Amplifier Output (V)	GAIN SETTING 3 Bit Value	GAIN SETTING 4 Amplifier Output (V)	GAIN SETTING 4 Bit Value	GAIN SETTING 5 Amplifier Output (V)	GAIN SETTING 5 Bit Value
0	0.0	-1.1	1.09	2265	1.84	2415	2.07	2462	2.28	2503	2.39	2526
1	1.0	0.3	0.66	2178	0.47	2142	0.42	2132	0.38	2119	0.34	2115
2	2.0	1.7	0.23	2092	-0.88	1872	-1.22	1803	-1.52	1742	-1.70	1707
3	2.9	3.0	-0.21	2006	-2.25	1596	-2.88	1468	-3.46	1355	-3.76	1295
4	3.9	4.3	-0.64	1919	-3.60	1326	-4.52	1143	-5.34	977	-5.80	886
5	4.9	5.7	-1.07	1832	-4.97	1052	-6.17	811	-7.24	597	-7.83	480
6	5.9	7.1	-1.54	1739	-6.42	760	-7.94	457	-9.28	188	-10.02	42
7	6.9	8.5	-1.95	1656	-7.73	498	-9.53	139	-10.72	0	-10.72	0
8	7.8	9.9	-2.39	1568	-9.10	225	-10.72	0	-10.72	0	-10.72	0
9	8.8	11.1	-2.60	1525	-9.77	90	-10.72	0	-10.72	0	-10.72	0
10	9.8	12.5	-2.61	1525	-9.77	90						
11	10.9	13.9	-2.61	1525	-9.77	90						

APPLIED LOAD & WHEATSTONE BRIDGE OUTPUT

mass (x 0.1 kg)	weight (N)	output (mV)
0	0.0	-1.06
1	1.0	0.30
2	2.0	1.66
3	2.9	3.00
4	3.9	4.35
5	4.9	5.71
6	5.9	7.07
7	6.9	8.48
8	7.8	9.85
9	8.8	11.14
10	9.8	12.52
11	10.8	13.89

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APPLIED LOAD & AMPLIFIER OUTPUT

mass (x 0.1 kg)	weight (N)	Amplifier Input (mV)	Output for Gain Setting: 1 (V)	2 (V)	3 (V)	4 (V)	5 (V)
0	0.0	-1.06	1.09	1.84	2.07	2.28	2.39
1	1.0	0.30	0.66	0.47	0.42	0.38	0.34
2	2.0	1.66	0.23	-0.88	-1.22	-1.52	-1.70
3	2.9	3.00	-0.21	-2.25	-2.88	-3.46	-3.76
4	3.9	4.35	-0.64	-3.60	-4.52	-5.34	-5.80
5	4.9	5.71	-1.07	-4.97	-6.17	-7.24	-7.83
6	5.9	7.07	-1.54	-6.42	-7.94	-9.28	-10.02
7	6.9	8.48	-1.95	-7.73	-9.53	-10.72	-10.72
8	7.8	9.85	-2.39	-9.10	-10.72	-10.72	-10.72
9	8.8	11.14	-2.60	-9.77	-10.72	-10.72	-10.72
10	9.8	12.52	-2.61	-9.77			
11	10.8	13.89	-2.61	-9.77			

AMPLIFIER INPUT & OUTPUT VALUES

mass (x 0.1 kg)	weight (N)	Gain Setting 1 (mV)	Gain Setting 1 (V)	Gain Setting 2 (mV)	Gain Setting 2 (V)	Gain Setting 3 (mV)	Gain Setting 3 (V)	Gain Setting 4 (mV)	Gain Setting 4 (V)	Gain Setting 5 (mV)	Gain Setting 5 (V)
0	0.0	-1.06	1.09	-1.06	1.84	-1.06	2.07	-1.06	2.28	-1.06	2.39
1	1.0	0.30	0.66	0.30	0.47	0.30	0.42	0.30	0.38	0.30	0.34
2	2.0	1.66	0.23	1.66	-0.88	1.66	-1.22	1.66	-1.52	1.66	-1.70
3	2.9	3.00	-0.21	3.00	-2.25	3.00	-2.88	3.00	-3.46	3.00	-3.76
4	3.9	4.35	-0.64	4.35	-3.60	4.35	-4.52	4.35	-5.34	4.35	-5.80
5	4.9	5.71	-1.07	5.71	-4.97	5.71	-6.17	5.71	-7.24	5.71	-7.83
6	5.9	7.07	-1.54	7.07	-6.42	7.07	-7.94	7.07	-9.28	7.07	-10.02
7	6.9	8.48	-1.95	8.48	-7.73	8.48	-9.53	8.48	-10.72	8.48	-10.72
8	7.8	9.85	-2.39	9.85	-9.10	9.85	-10.72	9.85	-10.72	9.85	-10.72
9	8.8	11.14	-2.60	11.14	-9.77	11.14	-10.72	11.14	-10.72	11.14	-10.72
10	9.8	12.52	-2.61	12.52	-9.77	12.52		12.52		12.52	
11	10.8	13.89	-2.61	13.89	-9.77	13.89		13.89		13.89	

APPLIED LOAD & ADC CARD OUTPUT

mass (x 0.1 kg)	weight (N)	Gain Setting 1 (V)	Gain Setting 1 Bit Value	Gain Setting 2 (V)	Gain Setting 2 Bit Value	Gain Setting 3 (V)	Gain Setting 3 Bit Value	Gain Setting 4 (V)	Gain Setting 4 Bit Value	Gain Setting 5 (V)	Gain Setting 5 Bit Value
0	0.0	1.09	2265	1.84	2415	2.07	2462	2.28	2503	2.39	2526
1	1.0	0.66	2178	0.47	2142	0.42	2132	0.38	2119	0.34	2115
2	2.0	0.23	2092	-0.88	1872	-1.22	1803	-1.52	1742	-1.70	1707
3	2.9	-0.21	2006	-2.25	1596	-2.88	1468	-3.46	1355	-3.76	1295
4	3.9	-0.64	1919	-3.60	1326	-4.52	1143	-5.34	977	-5.80	886
5	4.9	-1.07	1832	-4.97	1052	-6.17	811	-7.24	597	-7.83	480
6	5.9	-1.54	1739	-6.42	760	-7.94	457	-9.28	188	-10.02	42
7	6.9	-1.95	1656	-7.73	498	-9.53	139	-10.72	0	-10.72	0
8	7.8	-2.39	1568	-9.10	225	-10.72	0	-10.72	0	-10.72	0
9	8.8	-2.60	1525	-9.77	90	-10.72	0	-10.72	0	-10.72	0
10	9.8	-2.61	1525	-9.77	90						
11	10.8	-2.61	1525	-9.77	90						

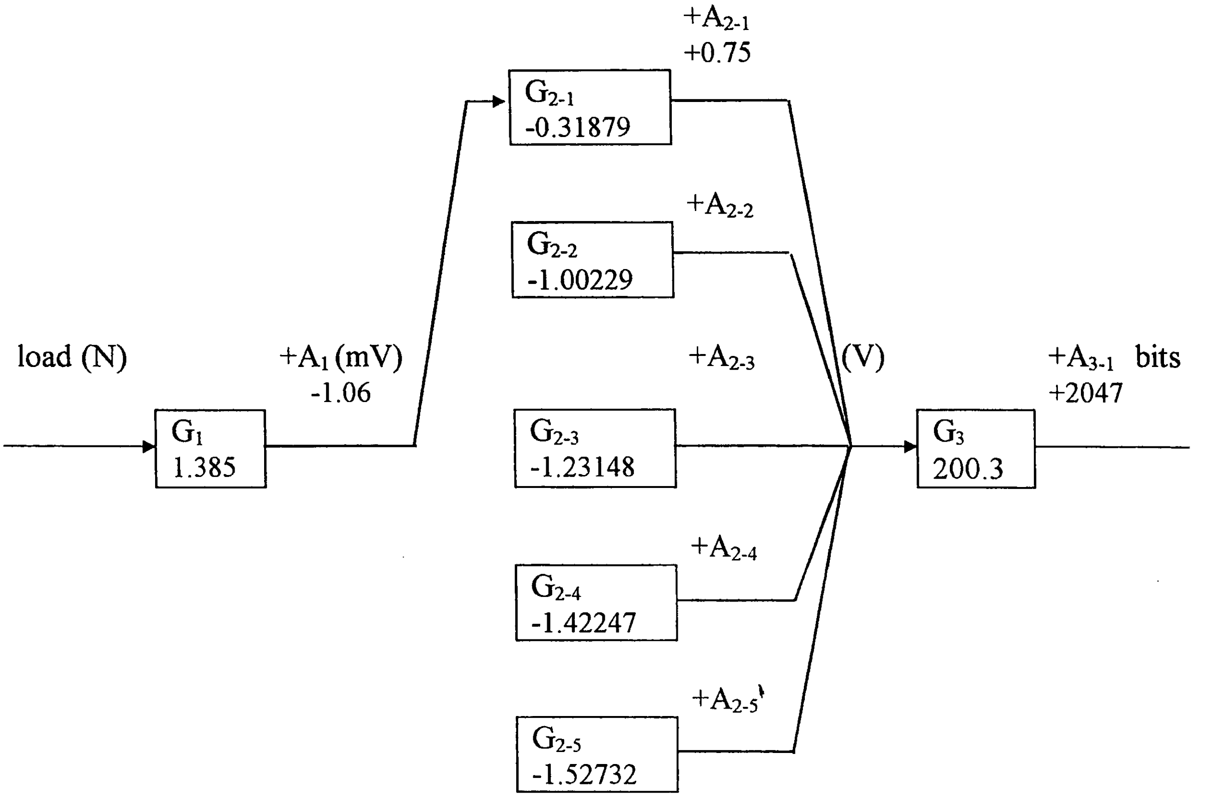
Table of results for calculation of transfer functions

table 5.15

The calculated magnitudes of the transfer functions, and their associated offset values, for each element are;

G_1 = 1.385 (mV/N)	A_1 = -1.06 (mV)		
G_{2-1} = -0.31879 (V/mV)	A_{2-1} = 0.75 (V)	maximum input = 9.85 mV
G_{2-2} = -1.00229 (V/mV)		maximum input = 9.85 mV
G_{2-3} = -1.23148 (V/mV)		maximum input = 8.48 mV
G_{2-4} = -1.42247 (V/mV)		maximum input = 7.066 mV
G_{2-5} = -1.52732 (V/mV)		maximum input = 7.066 mV
G_{3-1} = 200.284 (bits/V)	A_{3-1} = 2047 (bits)	

These values are shown in figure 5.46



Calculated values of transfer functions and adjustment offsets – single actuator
figure 5.46

An example of the signal 'flow' for the application of a 5.89 N compressive load (mass of 600 gm) is shown below.

For G_1 (load cell)
5.886 (N) *(i.e. 600 gm)* x G_1 (1.385 mV/N) + A_1 (-1.06 mV)
= 7.092 mV (compared with 7.066 mV recorded)
For G_{2-1} (amplifier)
7.066 (mV) x G_{2-1} (-0.31879 V/mV) + A_{2-1} (0.75 V)
= -1.5026 V (compared with -1.535 V recorded)
For G_3 (ADC board)
-1.535 (V) x G_{3-1} (200.284 bits/volt) + 2047 (bits)
= 1739 bits (compared with 1739 recorded)

Amplifier Gain Values

Using a nominal applied load on the transducer of 16 (N) compressive, the transducer output would be 22.16 (mV), for the measured transducer sensitivity of 1.385 (mV/N). The nominal required amplifier gain would be 10 (V) / 22.16 (mV), i.e. 451, to provide an output voltage of 10 volts, ignoring the offset adjustments.

The gain of the pre-amplifier was 100 so the overall gain of both amplifiers (determined from an examination of the circuit components) is given by:

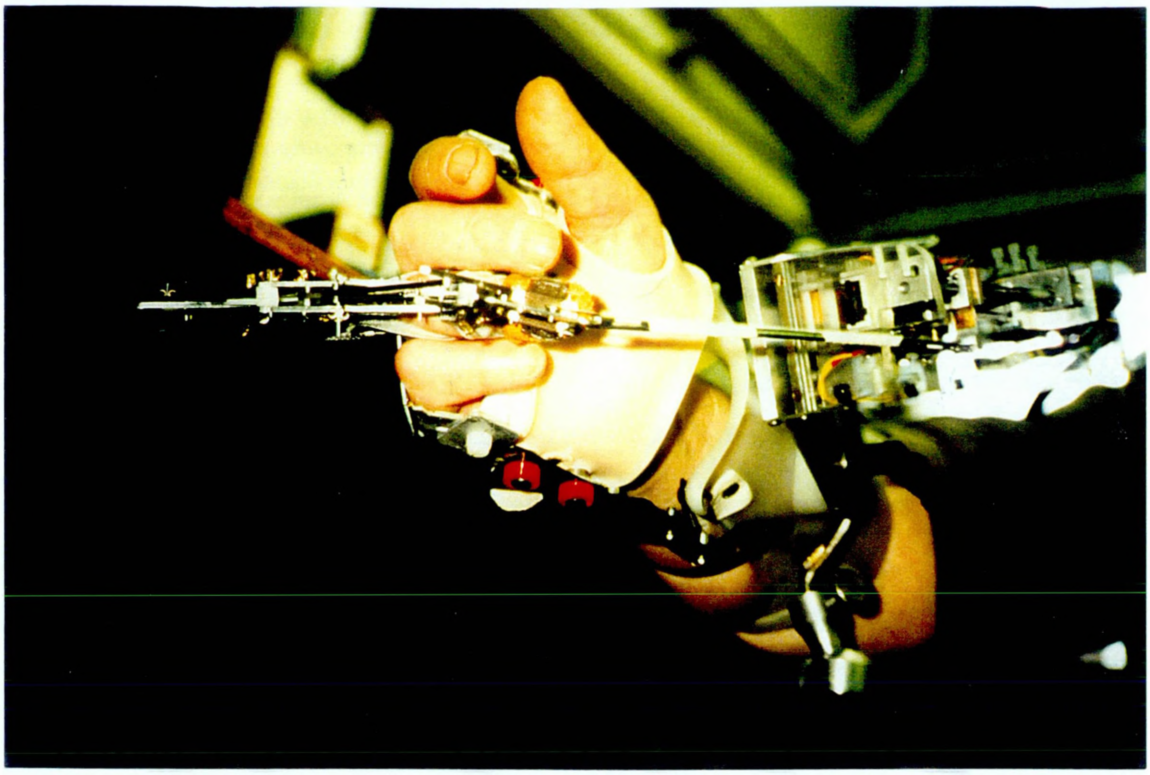
$$\frac{75K}{R_1} \times 100 = 474$$

The preferred R_1 is 16.63 kOhms for a compressive load of 0 - 16 Newtons. The required values of all the resistors R_1 are:

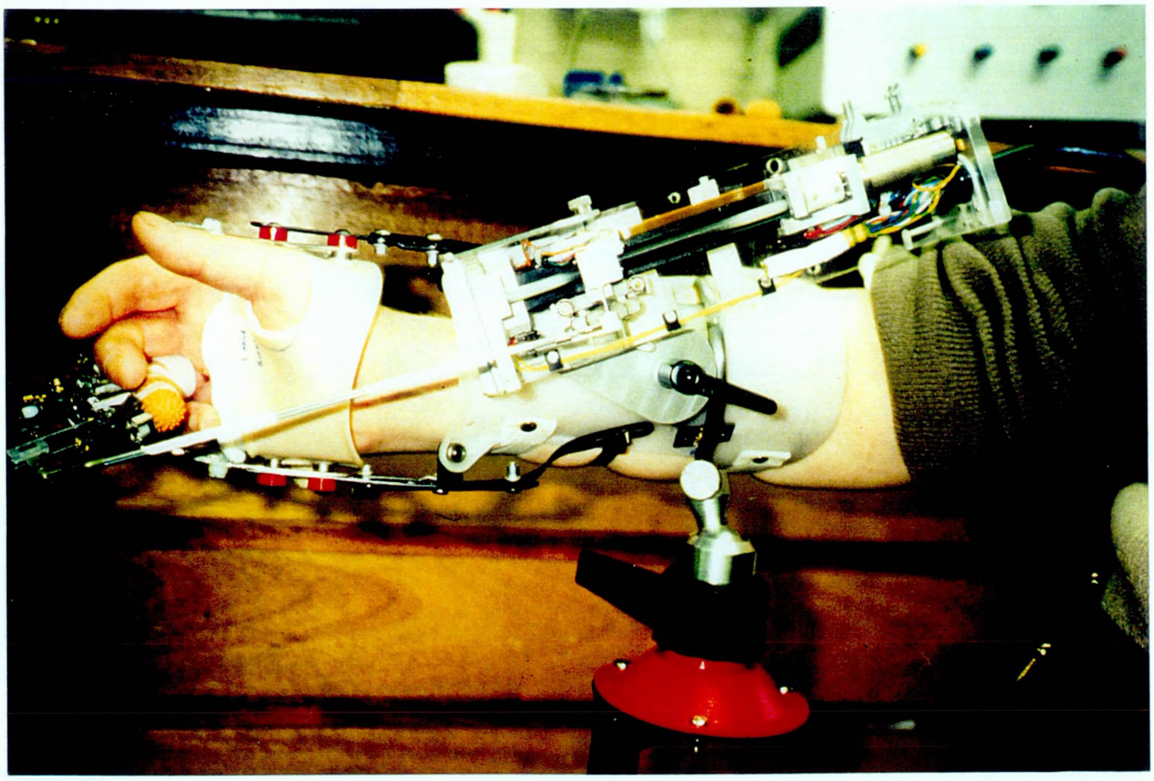
applied load (N)	required 2nd stage gain	value for R_1	amplifier external switch position
0 - 16	4.51	16.63 K	1
0 - 13	5.55	13.51 K	2
0 - 10	7.22	10.39 K	3
0 - 7	10.31	7.28 K	4
0 - 4	18.04	4.16 K	5

5.6.5 Application of the single actuator machine on a patient

Figures 5.47 and 5.48 shows the application of the machine on a patient, with the actuator's line of action parallel to the natural plane of movement of a finger towards the scaphoid, to avoid torsional effects at the MCP joint. This arrangement could be provided because the actuator was supported in a perspex case fixed to a plastic splint that had three degrees of freedom with respect to the patient's forearm. These were its angle of tilt (to accommodate varying wrist angles), its transverse position and its radial angle with respect to the longitudinal axis of the forearm (to provide for a line of action of its actuating rod over the scaphoid towards the finger tip). The splint could be locked in a universal joint fixed to the armrest of a chair. When comfortably seated, the patient's arm would be strapped into the splint and the actuating rod applied to the finger.



Photograph of machine; actuator's line of action parallel to the natural plane of finger movement
figure 5.47

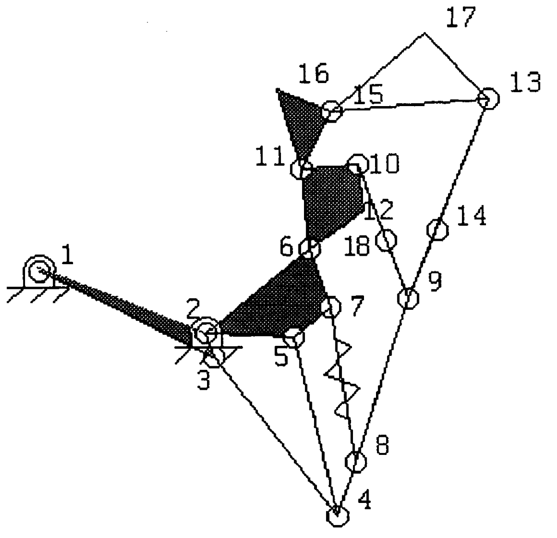


Patient using single actuator machine
figure 5.48

CHAPTER 6
EXPERIMENTAL METHOD, DATA COLLECTION AND PROCESS OF DATA

6.1 Anthropometric study of finger bone lengths

The development of the finger linkage model was described in section 5.5. The definitive model was shown in figure 5.24 (page 133) and is reproduced in figure 6.1 below.



Model of definitive linkage used for patient tests
figure 6.1

A risky aspect of its development was the decision to include the phalanges as integral parts because the linkage's kinematic behaviour would be affected by their sizes. The sensitivity of these different sizes would have to be tested.

Data were identified for the overall lengths of the fingers (e.g. Bailey, 1982) but what was required were the distances between the *centres of rotation* of the phalanges. It was felt that a study of finger bone lengths was necessary for the development of linkage model. The Anatomy Department at Dundee University offered assistance by providing the skeletal specimens and also advice on the methods for making measurements, described in the reference book, 'A laboratory manual of anthropometry', by Wilder, H.H. (1920).

This section describes the study. Its results were used to test the sensitivity of the linkage's kinematic behaviour (described in section 5.5.4.2, page 144) when applied to each of the four fingers.

6.1.1 Method

Thirty dried adult skeletal hands, which had previously been stripped of soft tissue, were made available for the study. The sex of each skeleton was not known but this was not considered to be significant since a single size of CPM machine would be made for patients of both sexes.

The following lengths were carefully recorded;

- The anatomical *maximum lengths* of the thumb and finger phalanges, including all processes and ridges. This data is shown in table 6.1
- The *physiological lengths*, namely the distance from the centre of depression of the articular surface at one end to the articular surface at the opposite end of the phalanx, in the manner described by Wilder (1920). This data is shown in table 6.2
- The *overall length* of each phalanx, and the head of its proximal phalanx, when they are articulated together and held in a flexed position. These lengths are shown as L2 in figure 6.4 (for the distal phalanx), and L4 in figure 6.5 (for the middle phalanx). Both these figures are shown on page 175. This data is shown in table 6.3.

6.1.2 Process of data

The data in tables 6.1, 6.2 and 6.3 were used to compute the ratios of proximal/distal finger bone lengths (both anatomical maximum and physiological lengths) and the results are shown in tables 6.4 and 6.5.

Ratios of anatomical maximum lengths of the phalanges

The mean ratios of anatomical maximum lengths of adjacent phalanges were extracted from table 6.4 and they are listed, with their standard deviation values, in table 6.6.

	Index	*Middle*	*Ring*	*Little*
DP/MP	0.728 (0.085)	0.646 (0.048)	0.655 (0.069)	0.824 (0.082)
MP/PP	0.614 (0.055)	0.667 (0.044)	0.667 (0.038)	0.617 (0.070)
PP/MC	0.603 (0.030)	0.709 (0.041)	0.744 (0.045)	0.640 (0.058)

Ratios of anatomical maximum lengths for the phalanges
table 6.6

ANATOMICAL MAXIMUM LENGTHS OF PHALANGES INCLUDING PROCESSES AND RIDGES

		thumb			index				middle				ring				little			
		dp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc
HAND 1	right	21.25	28.5	43.5	15.25	22	38.5	62.75	16.5	27.75	44	58.25	16	26.5	40.25	53.25	15	18	32.75	49
HAND 2	right	21.5	30.25	43	16.5	20.75	36	62	18	26	40.5	57.75	16.75	26	36.5	51.25	17.5	19.5	31.5	49
HAND 3	right	19.25	29	46.5	17.75	23.25	39	68.25	17.75	27.75	41	62.25	17.75	26.5	44	57.25	17.25	19	30.75	51.25
HAND 4	left	18.25	25.25	38.25	14.75	19.5	34	58	14.5	24.25	38.25	54.25	15	23	35	49	13	15.5	27.75	44.25
HAND 5	left	20	26.25	40.5	15.5	21.75	36.5	60.5		28.25	40.75	55.25	16.25	26.25	38.25	48.25	13.5	19.5	31	45.5
HAND 6	right	22.25	30	41.25	15.25	22.25	38	64.25	16.25	28.25	43	58.75	16	27	40	51.25	14.75	18.25	31.25	49
HAND 7	right	23	31.25	46	17.5	23.75	41.75	71	18	28.5	44.5	66	19.25	27	41.25	59	17.5	19	33	55
HAND 8	left	22.75	31.75	45.5	17.5	24.5	40.25	65.75	18.25	29.5	44.75	59.75	18.75	28.5	42.25	51.75			33.5	43.25
HAND 9	left	19.5	27.5	42.5	16.5	19.25	37.5	64.25	16	24.75	42.75	62.75	16.25	25	38.25	54		18	29.5	49.25
HAND 10	left	21.25	28	45.75	18	27.75	41	67.25	18.25	22.5	38.75	64.5	16.75	23.75	39	57.25	16.75	20.75	33.25	53.25
HAND 11	right	21.5	28.5	44.75	15	22	37.25	65.75	18.25	28.25	41.5	60	16.5	27.5	39	54.5	14.75	17.25	31.75	50.25
HAND 12	right	23.5	31.75	42.25	16.75	22.75	38	65.75	17.75	28.25	43.25	58.25	17	26.25	40.75	53.25	16.75	18.25	31.75	49.25
HAND 13	right	20.75	31.25	44.75	16.75	23.5	40	67.75	18.75	28	45	61.25	17	27	41.25	56.75	16.25	18.25	32.25	52
HAND 14	right	21	28.75	44.5	16	23.25	39	67.25		28.75	42.75	62.75	16.25	26.25	40.5	56.25		17.5	31.25	49
HAND 15	right		29	44.25	17.75	22	36.75	62.5	18.5	27.75	41.75	57	18.5	27.75	40.25	52	15.25	18.25	30.75	50.75
HAND 16	left	24.5	33.25	47.25	18.5	24.75	40.25	68.25	19.25	30.25	45.5	63.25	17.75	29.75	43.5	55.25	17	21.25	34.25	53.5
HAND 17	left	22.25	30.75	41.75	17.75	24.75	38.75	65	18	29.5	42	58.5	16.75	28	39.5	53.75	16.25	20.25	31.25	51.25
HAND 18	left	21.5	32.75	46.5	19.5	28.5	40.5	68	20	30.5	44	62.5	19.25	26	35.75	55.25	15	20	32.75	53.5
HAND 19	right	22.5	29.25	47.25	16	24.25	41.75	68	18.5	29.75	47.75	64.25	17.25	28.25	42.25	61.25	16	20.5	34.25	51
HAND 20	left	22	28	42	17.5	21.25	34.75	61.25	19	29.25	42.5	56.25	16.5	29.75	43	49.5	15	16.75	30	49.5
HAND 21	left	20.25	29.75	41.5	20.25	20.5	39.25	61.75	18.25	29	44.25	57.75	18.5	26.25	40	52.25	15.25	18.25	29.75	50.25
HAND 22	right	21.25	32.5	45.5	21.75	25.5	41.25	65.75	18.25	28.5	41.25	61.25	22	24.25	39	52	17.5	20	40	50.25
HAND 23	left	23.25	30.25	42.75	19	33	44.25	66	19.25	30.25	40.75	58.25	18.5	27.25	39.5	53.25	18	20.25	24	51
HAND 24	right	23	29	41.75				68.25	21.25	30.5	43.25	65.75		24	40	56.5	16.25	21	30	49.75
HAND 25	right	25.25	32.25	46.25	19	27	40	68.5	21.25	30.5	44	64	18.25	29.25	42	58.25	16.25	22.5	33	54
HAND 26	left	25	34.5	48.75	21	29	46	73.5	20.5	32	49.5	66	20.25	28	46.75	61	16.75	29	37.75	56.25
HAND 27	left	25.25	36	49	21.25	33	48	70	20	33.25	43.5	64.75	19.25	27.25	42	58.75	17.5	24.25	34.25	54.5
HAND 28	right	23.25	31.25	43.25	16.75	29.25	39.75	62.5	18.75	25.75	42.75	57	17.5	28	40.25	53	17.5	20.5	33.25	50.75
HAND 29	left	23.25	30	47	17.5	26	41.5	64.25	18.5	31.25	45.5	59.5	17	30.75	40.75	51	16.75	20.75	34.5	48.5
HAND 30	right	24	32	48	17.5	23.5	41	72	19.75	31	41.25	64.25	19.5	27.75	42.75	58.5	18.25	19.25	31.25	51.75
	SUM	642.25	908.5	1331.8	510	708.5	1150.5	1976	517.25	859.75	1290.25	1822	512.25	808.75	1213.5	1634.5	437.5	571.5	962.25	1515.75
	MEAN	22.147	30.283	44.392	17.5862069	24.4310345	39.6724138	65.8666667	18.4732143	28.6583333	43.0083333	60.7333333	17.6637931	26.9583333	40.45	54.4833333	16.2037037	19.7068966	32.075	50.525
	S D	1.7885	2.344	2.6365	1.86877044	3.56939905	3.03484485	3.54632722	1.49279021	2.30860771	2.37759235	3.39937452	1.52841518	1.80407027	2.43572548	3.44972096	1.3409903	2.52228369	2.84676919	2.91942809

Anatomical maximum lengths of phalanges including processes and ridges
table 6.1

PHYSIOLOGICAL LENGTH OF PHALANGES (effective phalangeal lengths measured between the centres of pressure of the articular surfaces)

		thumb			index				middle				ring				little			
		dp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc
HAND 1	right	19.75	26.75	42.25	15	20.5	37	61.25	15.75	27	42.5	57.75	15.25	24.25	39.75	53.25	14.25	17.25	31	48.5
HAND 2	right	19.5	27.25	41.5	15.75	19.75	34.75	60.5	17.5	25.25	39	57.75	16	24	36.25	50.75	15.5	19.25	30	47.25
HAND 3	right	17.75	27	44.75	16.25	21.75	37	64.25	17	25.25	38.5	62	17.75	24.5	42.25	56	15.5	17.25	28.5	50
HAND 4	left	17.25	23.25	37	14.25	19	32.5	56.75	14	23	37.25	53.25	14	21.5	35	48.25	12.5	14.75	27	43.5
HAND 5	left	18.75	24.5	38.25	13	19.75	34.75	58.5		25.25	39.75	54.75	14.75	24	37.25	47.75	12.25	16.25	28.75	44
HAND 6	right	20.25	27.75	40.5	15	22	37	61.5	16	26.5	41.75	58.25	15.75	25.25	39.25	50.75	14.5	17.25	29.25	49
HAND 7	right	21.75	29	44.25	17	22.5	40	68	17.25	26.75	43.25	65.75	18	25.5	40.5	58.25	16.25	17.5	31.75	53
HAND 8	left	21.5	29	43.5	16.5	22	38.25	60.75	17.75	27.5	43.25	58.75	18.25	27	40.5	51.25			32	43.25
HAND 9	left	19.25	25	41.5	15	18.25	34.75	61	15.5	23.25	40.5	60.75	15	22.75	37.5	54		15.5	28.5	48.25
HAND 10	left	20	27	44	17	26.5	40.5	65.75	18	22.25	36.25	64.5	16	21.75	37	56.5	14.5	19.25	32	53
HAND 11	right	20.25	27.75	42.5	14.5	20.25	35	62.25	17	26	40	59.5	15.75	24.5	37.75	54	14.25	15.5	29.75	50.25
HAND 12	right	22	28.75	41.5	15.5	22	36	61.75	16.75	26.25	41.75	58	16	24.25	38.75	51.5	15.75	17.25	30	48.75
HAND 13	right	19	27.75	42.5	15.75	22.25	38.25	66.25	16.75	27.25	43.5	60.5	16.5	25	40	56.5	15	16.5	31.25	50
HAND 14	right	19	27.5	43.25	15	21.5	35.25	65.5		28.5	41.25	62.25	15.75	24.5	39.25	54.75		16.25	29	49
HAND 15	right		27.25	43	16.25	20.25	34.75	59.5	18.5	26	39.75	37	17	25.25	38.25	52	15.25	16.25	29.75	47.5
HAND 16	left	22	30.25	45	17.25	23.75	39.25	65.75	19.25	28.75	44.25	62.75	17.5	27.75	43.25	55	16.75	20.5	34	53
HAND 17	left	21	27.75	39.75	17	22.75	36.75	61.25	17	27.25	40.25	58.5	16.25	26.5	39.25	52.5	15.75	18.25	30.25	49.75
HAND 18	left	21.25	29.75	45.25	18.75	26.5	39.25	65	18.25	29	42.25	62.5	18.25	24.5	33.5	55	14	19.25	31.75	51.5
HAND 19	right	21	27.25	45	15	22.5	39.75	66	17.75	28	46	63.75	16.5	26.75	40.75	59.75	15.25	18.25	33.25	51
HAND 20	left	20.5	26.75	40.75	16.75	18.75	33	57.75	18.25	28.25	41.75	56.25	16	28	40.75	48.75	14	15	29.5	48.25
HAND 21	left	19.25	28.25	41.25	19	22.75	38	60	17.75	27.75	41.75	57.75	16	24.75	38.75	50.75	14.75	17.25	29	49
HAND 22	right	21.25	30	44.75	20.75	24.25	38.25	62.75	18	26.5	40	59.75	20.75	22.75	38.25	52	16.5	19.25	37.75	49.5
HAND 23	left	20.75	27.75	41.25	18	30.75	43.25	62.75	18.5	28	39.5	58.25	17.5	26.5	37.75	53.25	16.75	18.5	22.5	50.75
HAND 24	right	21	28	40.25				64.75	19.5	28.25	41.5	63.25		23.75	39.5	56.5	15.25	19.25	28.75	48.5
HAND 25	right	23.75	29.75	44.25	18	25.75	38.75	65.5	19.25	28.5	43.25	63.5	17.25	27.25	41	57.75	15.75	21.5	32.5	53
HAND 26	left	23.25	31.75	45.5	19.75	26.75	43.5	68.5	19.25	30	48.25	66	20	26	44	58.75	16.75	26.75	35.75	54.5
HAND 27	left	23.5	32	46.25	19.75	30.75	44	65.5	19	31	41	63	18	25	39	57.75	17	21.5	32.5	53
HAND 28	right	22.5	28	42	16.75	26.75	38.75	58	17	22.75	40.75	57	16.5	25.5	38.25	52.25	16.5	19	31.25	48.75
HAND 29	left	21.25	27.5	44	17.25	24	39	61.25	17.25	29	43	58.5	17	28.75	39.75	51	16	20	32	46.25
HAND 30	right	21.25	28.75	44	16.25	23.25	40	68	18.5	29.5	41.25	63	18.5	26.75	41.75	55.5	17.5	18.75	31	51
	SUM	599.5	839	1279.5	482	667.5	1097.25	1886.25	492.25	808.5	1243	1784.5	487.75	754.5	1174.75	1612	414	529	920.25	1485
	MEAN	20.672	27.967	42.65	16.6206897	23.0172414	37.8362069	62.875	17.5803571	26.95	41.4333333	59.4833333	16.8189655	25.15	39.1583333	53.7333333	15.3333333	18.2413793	30.675	49.5
	S.D	1.5939	1.8555	2.2105	1.80725311	3.22166982	2.91798293	3.23754244	1.27485215	2.16396826	2.41754839	5.30692997	1.4968666	1.76117124	2.24134671	3.19410376	1.29161497	2.43439157	2.73951764	2.75665339

Physiological lengths of phalanges
table 6.2

OVERALL LENGTH OF EACH PHALANGE AND THE HEAD OF THE PROXIMAL PHALANGE (joint held in a flexed position)

		thumb			index				middle				ring				little			
		dp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc
HAND 1	*right*	26.5			19.75	27.75			21.25	34.5			20	32			18	22.75		
HAND 2	*right*	29			21	27			22.75	32.5			21.5	31.5			19.5	25		
HAND 3	*right*	25.75			20.75	29.5			22.75	33.75			22	31.75			20	24.25		
HAND 4	*left*	22.5			18.25	26.75			19	29.75			18.25	28			16.75	20		
HAND 5	*left*	26			19	27				33			19.5	31.75			17	21.75		
HAND 6	*right*	28.5			20	28.5			21	33.25			21	31.5			18.25	22.5		
HAND 7	*right*	29.5			21.75	30			22.5	34.25			23	31.75			21	24		
HAND 8	*left*	29.5			21.75	30			23	35.5			23.25	34.5						
HAND 9	*left*	27.25			19.75	25.5			20.5	31.75			20	31				22.25		
HAND 10	*left*	28			21.5	33.75			22.75	29.5			21	30			19	25.75		
HAND 11	*right*	28.25			19.75	27.25			22.5	33			20.5	31.25			18	22.25		
HAND 12	*right*	30.25			21	29.5			22.25	34.25			21.5	32			19.5	22.5		
HAND 13	*right*	27.5			21	29			22.25	34.75			21.25	32.5			20	23.25		
HAND 14	*right*	26.5			20.25	29.25				35.25			20	32.25				22.75		
HAND 15	*right*				23	28.25			25	34.75			23.5	34			20	23.25		
HAND 16	*left*	30.5			23	31.25			24	36.75			23	37			21.25	27		
HAND 17	*left*	29.25			21.75	30.25			24	34.75			22	33.5			20.25	25		
HAND 18	*left*	30			24.5	34.75			25.25	36.75			24.25	31.25			18.25	25		
HAND 19	*right*	30			20.75	30			24.25	36.25			22.5	34.25			20	25.5		
HAND 20	*left*	29.5			22.5	27.25			24	35.25			20.75	35.75			18.25	21.25		
HAND 21	*left*	27.25			24.5	29			23.25	34			21	31.75			19.25	24.25		
HAND 22	*right*																			
HAND 23	*left*	31.25			25.25	41.5			24.75	37.25			23	36			23.25	26.5		
HAND 24	*right*																			
HAND 25	*right*	32.75			23.25	33.75			25.75	36			22.25	34			21	28		
HAND 26	*left*																			
HAND 27	*left*	32.25			27	41.75			24.25	39.75			25	34			22.75	30.25		
HAND 28	*right*																			
HAND 29	*left*																			
HAND 30	*right*																			

Overall length of each phalange and the head of the proximal phalange

table 6.3

RATIO OF MAXIMUM LENGTHS OF ADJACENT PHALANGES

		thumb		index			middle			ring			little		
		dp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc
HAND 1	*right*	0.75	0.66	0.69	0.57	0.61	0.59	0.63	0.76	0.60	0.66	0.76	0.83	0.55	0.67
HAND 2	*right*	0.71	0.70	0.80	0.58	0.58	0.69	0.64	0.70	0.64	0.71	0.71	0.90	0.62	0.64
HAND 3	*right*	0.66	0.62	0.76	0.60	0.57	0.64	0.68	0.66	0.67	0.60	0.77	0.91	0.62	0.60
HAND 4	*left*	0.72	0.66	0.76	0.57	0.59	0.60	0.63	0.71	0.65	0.66	0.71	0.84	0.56	0.63
HAND 5	*left*	0.76	0.65	0.71	0.60	0.60		0.69	0.74	0.62	0.69	0.79	0.69	0.63	0.68
HAND 6	*right*	0.74	0.73	0.69	0.59	0.59	0.58	0.66	0.73	0.59	0.68	0.78	0.81	0.58	0.64
HAND 7	*right*	0.74	0.68	0.74	0.57	0.59	0.63	0.64	0.67	0.71	0.65	0.70	0.92	0.58	0.60
HAND 8	*left*	0.72	0.70	0.71	0.61	0.61	0.62	0.66	0.75	0.66	0.67	0.82			0.77
HAND 9	*left*	0.71	0.65	0.86	0.51	0.58	0.65	0.58	0.68	0.65	0.65	0.71		0.61	0.60
HAND 10	*left*	0.76	0.61	0.65	0.68	0.61	0.81	0.58	0.60	0.71	0.61	0.68	0.81	0.62	0.62
HAND 11	*right*	0.75	0.64	0.68	0.59	0.57	0.65	0.68	0.69	0.60	0.71	0.72	0.86	0.54	0.63
HAND 12	*right*	0.74	0.75	0.74	0.60	0.58	0.63	0.65	0.74	0.65	0.64	0.77	0.92	0.57	0.64
HAND 13	*right*	0.66	0.70	0.71	0.59	0.59	0.67	0.62	0.73	0.63	0.65	0.73	0.89	0.57	0.62
HAND 14	*right*	0.73	0.65	0.69	0.60	0.58		0.67	0.68	0.62	0.65	0.72		0.56	0.64
HAND 15	*right*		0.66	0.81	0.60	0.59	0.67	0.66	0.73	0.67	0.69	0.77	0.84	0.59	0.61
HAND 16	*left*	0.74	0.70	0.75	0.61	0.59	0.64	0.66	0.72	0.60	0.68	0.79	0.80	0.62	0.64
HAND 17	*left*	0.72	0.74	0.72	0.64	0.60	0.61	0.70	0.72	0.60	0.71	0.73	0.80	0.65	0.61
HAND 18	*left*	0.66	0.70	0.68	0.70	0.60	0.66	0.69	0.70	0.74	0.73	0.65	0.75	0.61	0.61
HAND 19	*right*	0.77	0.62	0.66	0.58	0.61	0.62	0.62	0.74	0.61	0.67	0.69	0.78	0.60	0.67
HAND 20	*left*	0.79	0.67	0.82	0.61	0.57	0.65	0.69	0.76	0.55	0.69	0.87	0.90	0.56	0.61
HAND 21	*left*	0.68	0.72	0.99	0.52	0.64	0.63	0.66	0.77	0.70	0.66	0.77	0.84	0.61	0.59
HAND 22	*right*	0.65	0.71	0.85	0.62	0.63	0.64	0.69	0.67	0.91	0.62	0.75	0.88	0.50	0.80
HAND 23	*left*	0.77	0.71	0.58	0.75	0.67	0.64	0.74	0.70	0.68	0.69	0.74	0.89	0.84	0.47
HAND 24	*right*	0.79	0.69				0.70	0.71	0.66		0.60	0.71	0.77	0.70	0.60
HAND 25	*right*	0.78	0.70	0.70	0.68	0.58	0.70	0.69	0.69	0.62	0.70	0.72	0.72	0.68	0.61
HAND 26	*left*	0.72	0.71	0.72	0.63	0.63	0.64	0.65	0.75	0.72	0.60	0.77	0.58	0.77	0.67
HAND 27	*left*	0.70	0.73	0.64	0.69	0.69	0.60	0.76	0.67	0.71	0.65	0.71	0.72	0.71	0.63
HAND 28	*right*	0.74	0.72	0.57	0.74	0.64	0.73	0.60	0.75	0.63	0.70	0.76	0.85	0.62	0.66
HAND 29	*left*	0.78	0.64	0.67	0.63	0.65	0.59	0.69	0.76	0.55	0.75	0.80	0.81	0.60	0.71
HAND 30	*right*	0.75	0.67	0.74	0.57	0.57	0.64	0.75	0.64	0.70	0.65	0.73	0.95	0.62	0.60
	SUM	21.20207	20.4730122	21.0998802	17.802587	17.4860354	18.0906865	19.9964326	21.280841	18.9961861	20.0165135	22.3156356	22.2372816	17.8908716	19.0781756
	MEAN	0.73110586	0.68243374	0.72758208	0.61388231	0.60296674	0.64609595	0.66654775	0.70936137	0.6550409	0.66721712	0.74385452	0.82360302	0.61692661	0.63593919
	S.D.	0.03910843	0.03825096	0.0847024	0.05546046	0.03005041	0.04754467	0.04424941	0.04084392	0.06910833	0.0379226	0.04503225	0.08214139	0.06995245	0.05759204

Ratio of maximum lengths of adjacent phalanges
table 6.4

RATIO OF PHYSIOLOGICAL LENGTHS OF ADJACENT PHALANGES (from table 6)

		thumb		index			middle			ring			little		
		dp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc
HAND 1	*right*	0.74	0.63	0.73	0.55	0.60	0.58	0.64	0.74	0.63	0.61	0.75	0.83	0.56	0.64
HAND 2	*right*	0.72	0.66	0.80	0.57	0.57	0.69	0.65	0.68	0.67	0.66	0.71	0.81	0.64	0.63
HAND 3	*right*	0.66	0.60	0.75	0.59	0.58	0.67	0.66	0.62	0.72	0.58	0.75	0.90	0.61	0.57
HAND 4	*left*	0.74	0.63	0.75	0.58	0.57	0.61	0.62	0.70	0.65	0.61	0.73	0.85	0.55	0.62
HAND 5	*left*	0.77	0.64	0.66	0.57	0.59		0.64	0.73	0.61	0.64	0.78	0.75	0.57	0.65
HAND 6	*right*	0.73	0.69	0.68	0.59	0.60	0.60	0.63	0.72	0.62	0.64	0.77	0.84	0.59	0.60
HAND 7	*right*	0.75	0.66	0.76	0.56	0.59	0.64	0.62	0.66	0.71	0.63	0.70	0.93	0.55	0.60
HAND 8	*left*	0.74	0.67	0.75	0.58	0.63	0.65	0.64	0.74	0.68	0.67	0.79			0.74
HAND 9	*left*	0.77	0.60	0.82	0.53	0.57	0.67	0.57	0.67	0.66	0.61	0.69		0.54	0.59
HAND 10	*left*	0.74	0.61	0.64	0.65	0.62	0.81	0.61	0.56	0.74	0.59	0.65	0.75	0.60	0.60
HAND 11	*right*	0.73	0.65	0.72	0.58	0.56	0.65	0.65	0.67	0.64	0.65	0.70	0.92	0.52	0.59
HAND 12	*right*	0.77	0.69	0.70	0.61	0.58	0.64	0.63	0.72	0.66	0.63	0.75	0.91	0.58	0.62
HAND 13	*right*	0.68	0.65	0.71	0.58	0.58	0.61	0.63	0.72	0.66	0.63	0.71	0.91	0.53	0.63
HAND 14	*right*	0.69	0.64	0.70	0.61	0.54		0.69	0.66	0.64	0.62	0.72		0.56	0.59
HAND 15	*right*		0.63	0.80	0.58	0.58	0.71	0.65	1.07	0.67	0.66	0.74	0.94	0.55	0.63
HAND 16	*left*	0.73	0.67	0.73	0.61	0.60	0.67	0.65	0.71	0.63	0.64	0.79	0.82	0.60	0.64
HAND 17	*left*	0.76	0.70	0.75	0.62	0.60	0.62	0.68	0.69	0.61	0.68	0.75	0.86	0.60	0.61
HAND 18	*left*	0.71	0.66	0.71	0.68	0.60	0.63	0.69	0.68	0.74	0.73	0.61	0.73	0.61	0.62
HAND 19	*right*	0.77	0.61	0.67	0.57	0.60	0.63	0.61	0.72	0.62	0.66	0.68	0.84	0.55	0.65
HAND 20	*left*	0.77	0.66	0.89	0.57	0.57	0.65	0.68	0.74	0.57	0.69	0.84	0.93	0.51	0.61
HAND 21	*left*	0.68	0.68	0.84	0.60	0.63	0.64	0.66	0.72	0.65	0.64	0.76	0.86	0.59	0.59
HAND 22	*right*	0.71	0.67	0.86	0.63	0.61	0.68	0.66	0.67	0.91	0.59	0.74	0.86	0.51	0.76
HAND 23	*left*	0.75	0.67	0.59	0.71	0.69	0.66	0.71	0.68	0.66	0.70	0.71	0.91	0.82	0.44
HAND 24	*right*	0.75	0.70				0.69	0.68	0.66		0.60	0.70	0.79	0.67	0.59
HAND 25	*right*	0.80	0.67	0.70	0.66	0.59	0.68	0.66	0.68	0.63	0.66	0.71	0.73	0.66	0.61
HAND 26	*left*	0.73	0.70	0.74	0.61	0.64	0.64	0.62	0.73	0.77	0.59	0.75	0.63	0.75	0.66
HAND 27	*left*	0.73	0.69	0.64	0.70	0.67	0.61	0.76	0.65	0.72	0.64	0.68	0.79	0.66	0.61
HAND 28	*right*	0.80	0.67	0.63	0.69	0.67	0.75	0.56	0.71	0.65	0.67	0.73	0.87	0.61	0.64
HAND 29	*left*	0.77	0.63	0.72	0.62	0.64	0.59	0.67	0.74	0.59	0.72	0.78	0.80	0.63	0.66
HAND 30	*right*	0.74	0.65	0.70	0.58	0.59	0.63	0.72	0.65	0.69	0.64	0.75	0.93	0.60	0.61
	SUM	21.4241703	19.6739899	21.1047173	17.5814568	17.4690917	18.318015	19.5182478	21.0725617	19.4132148	19.2844924	21.9069709	22.6708012	17.3074228	18.6135686
	MEAN	0.73876449	0.65579966	0.72774887	0.60625713	0.60238247	0.65421482	0.65060826	0.70241872	0.6694212	0.64281641	0.73023236	0.8396593	0.59680768	0.62045229
	S.D	0.03342194	0.0288043	0.07005323	0.04623822	0.03430758	0.04736206	0.0404121	0.08079414	0.06566687	0.03777851	0.04559624	0.07700491	0.06899556	0.05283862

Ratio of physiological lengths of adjacent phalanges
table 6.5

Ratios of physiological lengths of phalanges:

Similarly, the mean ratios of physiological lengths of adjacent phalanges, with their standard deviations, were extracted from table 6.5 and they are listed, with their standard deviation values, in table 6.7 below.

	Index	Middle	Ring	Little
DP/MP	0.728 (0.070)	0.654 (0.047)	0.669 (0.066)	0.840 (0.077)
MP/PP	0.606 (0.046)	0.651 (0.040)	0.643 (0.038)	0.597 (0.069)
PP/MC	0.602 (0.034)	0.702 (0.081)	0.730 (0.046)	0.620 (0.053)

Ratios of physiological lengths of phalanges
(extracted from table 6.5)
table 6.7

It can be seen that from tables 6.6 and 6.7 that there are differences between the ratios of maximum and physiological phalangeal lengths. This emphasised the necessity to use physiological data for modelling purposes.

It was necessary to check that the sample size of thirty skeletal hands provided a frequency of measured bone length data which fitted reasonably well a normal distribution of data with the same mean and standard deviation values, though clearly an exact fit would be impossible to obtain. A normal frequency distribution is given by the expression;

$$f(x) = \frac{N}{\sigma\sqrt{2\pi}}.\exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right]$$

where N = number of data values; σ = standard deviation of data; x = class interval; m = mean value. This distribution was calculated for the ratios of physiological lengths of adjacent phalanges (table 6.5) and compared with the actual frequency distribution.

The method is illustrated with the example of the ratio of the middle:proximal phalangeal lengths for the middle finger (see seventh column of data in table 6.5). The relevant data is;

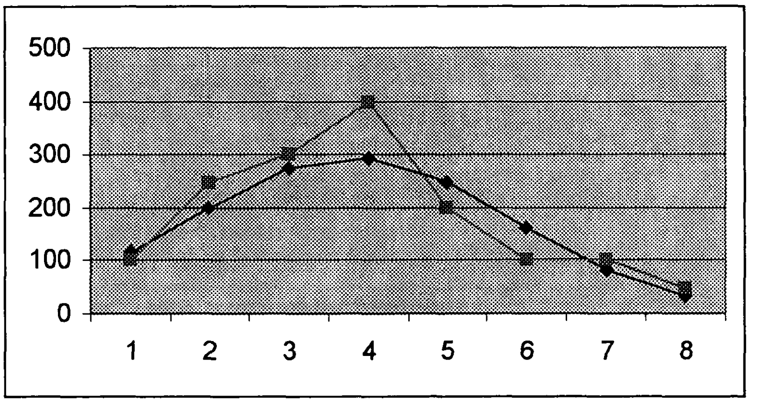
$N = 30$; $\sigma = 0.0404121$; $x =$ 0.595 (for data grouped between 0.585 and 0.605), 0.615 (for data grouped between 0.605 and 0.625), 0.635 (for data grouped between 0.625 and 0.645), etc; $m =$ 0.650606; $N/\sigma = 742.3538$;

Calculations were performed in the manner shown in table 6.8

specific class interval >	0.595	0.615	0.635	0.655	0.675	0.695	0.715	0.735
class frequency, f >	2	5	6	8	4	2	2	1
x - mean =	-0.05561	-0.03561	-0.01561	0.004392	0.024392	0.044392	0.064392	0.084392
t =ABS[(x-mean)/sd] =	1.37603	0.881129	0.386227	0.108674	0.603575	1.098476	1.593378	2.088279
exp (-0.5 *x* (t^2)) / sqrt (2.pi) =	0.154792	0.270595	0.370269	0.396593	0.332508	0.218217	0.1121	0.045077
class interval >	50							
class frequency f(y) = class interval *x* f =	100	250	300	400	200	100	100	50
normal frequency f(x) = (N/sigma) *x* exp (-0.5 *x* (t^2)) / sqrt (2.pi) =	115	201	275	294	247	162	83	33

Example of the method used to calculate the normal and actual frequencies of data distribution – middle finger middle/proximal phalangeal physiological lengths
table 6.8

These results are shown plotted in figure 6.2, which shows the normal frequency f(x) and the class frequency (i.e. the frequencies of the calculated ratios), f(y).



Normal and class (measured data) frequencies for the ratio of middle-to-proximal phalangeal lengths for the middle finger
figure 6.2

The results for all the ratios of phalangeal lengths were calculated in this manner and they are provided in table 6.9. Reasonably good fits to normal distribution curve were obtained, though the calculated ratios commonly showed a peak for the data with highest frequency of occurrence, similar to figure 6.2 above. It was concluded that the sample of skeletons was reasonably representative of a normal distribution, with the exception of the little finger for which the comparison is disappointing. The likely reason for this is the fact that the ratio of

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
ratio	0.505 - 0.525	0.525 - 0.545	0.545 - 0.565	0.565 - 0.585	0.585 - 0.605	0.605 - 0.625	0.625 - 0.645	0.645 - 0.665	0.665 - 0.685	0.685 - 0.705	0.705 - 0.725	0.725 - 0.745	0.745 - 0.765	0.765 - 0.785	0.785 - 0.805	0.805 - 0.825	0.825 - 0.845	0.845 - 0.865	0.865 - 0.885	0.885 - 0.905	0.905 - 0.925	0.925 - 0.945
INDEX																						
dp/mp f						1	3	1	2	4	4	3	5	0	2	1	1	1	1			
adj freq						50	150	50	100	200	200	150	250	0	100	50	50	50	50			
n.f						45	69	96	124	148	162	164	153	132	104	76	51	32	18			
mp/pp f		1	2	10	3	6	1	2	1	2	1											
adj freq		50	100	500	150	300	50	100	50	100	50											
n.f		76	135	199	243	246	206	144	83	40	16											
MIDDLE																						
dp/mp f				1	2	4	7	4	5	2	1	2										
adj freq				50	100	200	350	200	250	100	50	100										
n.f				58	108	167	217	236	214	163	104	55										
mp/pp f					2	5	6	8	4	2	2	1										
adj freq					100	250	300	400	200	100	100	50										
n.f					115	201	275	294	247	162	83	33										
RING																						
dp/mp				1	1	4	5	7	3	1	3	2	2									
adj freq				50	50	200	250	350	150	50	150	100	100									
n.f				63	93	125	154	172	176	163	138	107	75									
mp/pp f				1	4	4	9	5	3	2	1	1										
adj freq				50	200	200	450	250	150	100	50	50										
n.f				63	142	242	310	301	220	122	51	16										
LITTLE																						
dp/mp f											1	2	2	0	3	2	3	4	1	1	4	4
adj freq											50	100	100	0	150	100	150	200	50	50	200	200
n.f											38	56	76	98	118	133	140	137	126	108	87	65
mp/pp f	3	2	6	2	6	3	2	2	1	2												
adj freq	150	100	300	100	300	150	100	100	50	100												
n.f	83	112	140	160	168	162	144	117	88	61												

dp/mp f: frequency of ratio of distal to middle phalangeal lengths (centre-to-centre), within the stated range (row 2)
mp/pp f: frequency of ratio of middle to proximal phalangeal lengths (centre-to-centre), within the stated range (row 2)

adj freq : adjusted frequency for the calculated results
n.f. : normal frequency (i.e. for normal distribution)

Normal and actual frequencies of data distribution - ratios of physiological phalangeal lengths for each finger
table 6.9

distal:middle phalangeal lengths for the little finger is higher than for the other fingers because of its role in grasping actions, such as holding a hammer. It appears that there is a wider variation of bone lengths in the little finger than for the others.

6.1.3 Calculations to determine effective lengths of the phalanges

The 'effective length' of a phalanx is the distance between its distal and proximal axes of rotation. Formulae to calculate these lengths were developed using the following data;

(i) The physiological (not maximum) lengths of dried bones were taken from the study of thirty skeletons described earlier (tables 6.2 and 6.3).

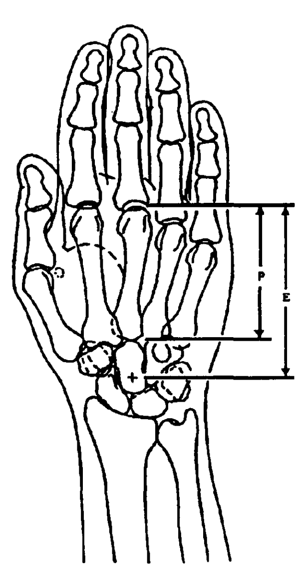
(ii) The interphalangeal joint space of 0.6 mm for the distal and proximal interphalangeal joints and 1.8 mm for the metacarpophalangeal joint were estimated from radiographs of normal adult hands (Snell and Wyman, 1976).

(iii) The location of the centre of rotation of the proximal phalanx about the metacarpal is situated at a point located 14% of the metacarpal's length from the articular head when flexed and 10% of this length when flexed (Snell and Wyman, 1976).

(iv) The centre of rotation of the wrist in both flexion/extension and abduction/ adduction is situated within the capitate at a point 71% of its length from the distal surface in the A-P view (Youm and Yoon, 1979). From figure 6.3, the ratio **E / P** is

$$\frac{\text{length of the 'extended' metacarpal from its distal end to the wrist axis}}{\text{physiological length of the metacarpal}}$$

where **E** and **P** are illustrated in figure 6.3. and the value **P** is taken from table 6.2.



effective and actual metacarpal lengths
figure 6.3

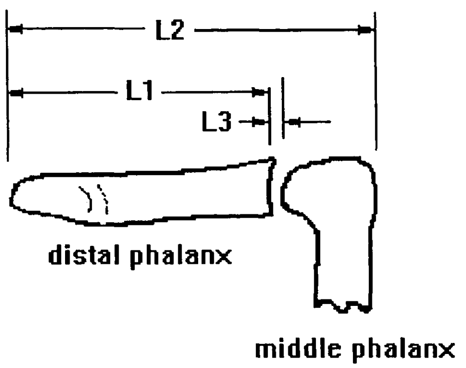
These ratios are;	1.29	for the index finger:	(R1)
	1.34	for the middle finger:	(R2)
	1.29	for the ring finger:	(R3)
	1.47	for the little finger:	(R4)

Using these ratio values, the effective lengths of the metacarpals (from their distal articular cartilage to the wrist axis) can be calculated. For example, the effective length of index finger metacarpal is;-

(RI - 0.14) * physiological length of the metacarpal

Effective lengths of finger bones, measured between joint centres:

Using these assumptions and the data in tables 6.2 and 6.3, the lengths of finger bones between joint centres were calculated using the following formulae;



Effective length of distal phalanx

L1: physiological length of the distal Phalanx

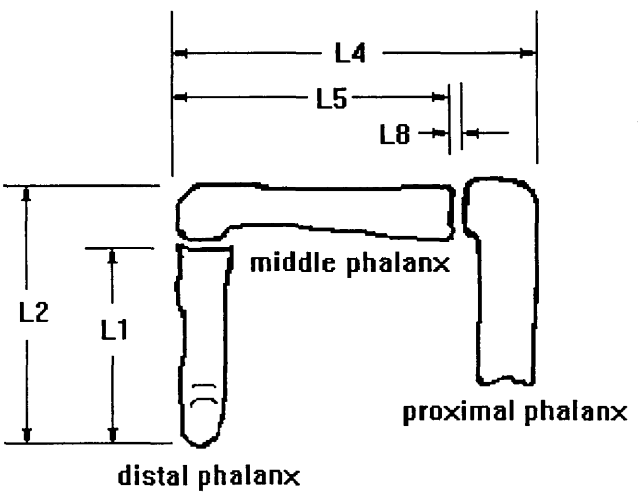
L2: overall length of distal phalanx and the Head of the middle phalanx, measured with dry skeletal bone and no cartilage

L3: distal interphalangeal joint space

length of distal phalanx =

L1 + ((L2-L1)/2) + L3

effective length of distal phalanx
figure 6.4



effective length of middle phalanx

L4: overall length of middle phalanx and the head of the proximal phalanx, measured with dry skeletal bone and no cartilage

L5: physiological length of the middle phalanx

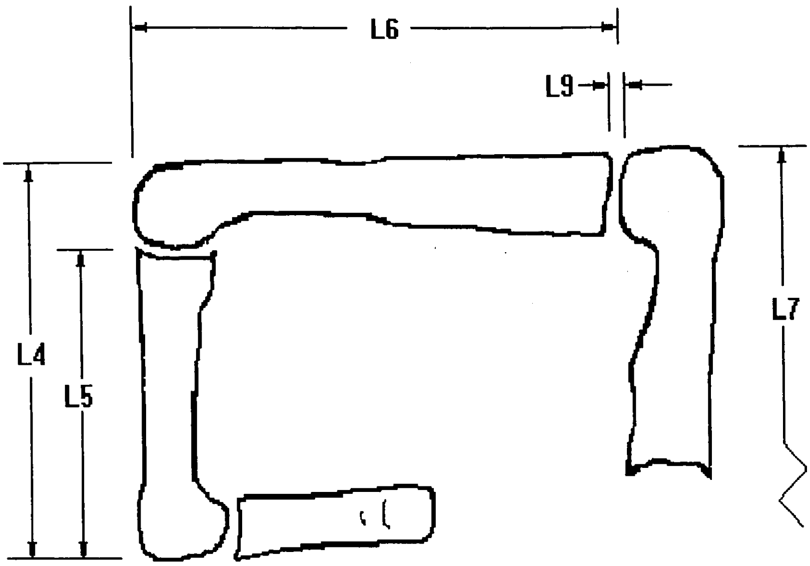
L8: proximal interphalangeal joint space

DIP - PIP joint distance =

L5 + ((L4-L5)/2) - ((L2-L1)/2) + L8

effective length of middle phalanx
figure 6.5

Effective length of proximal phalanx

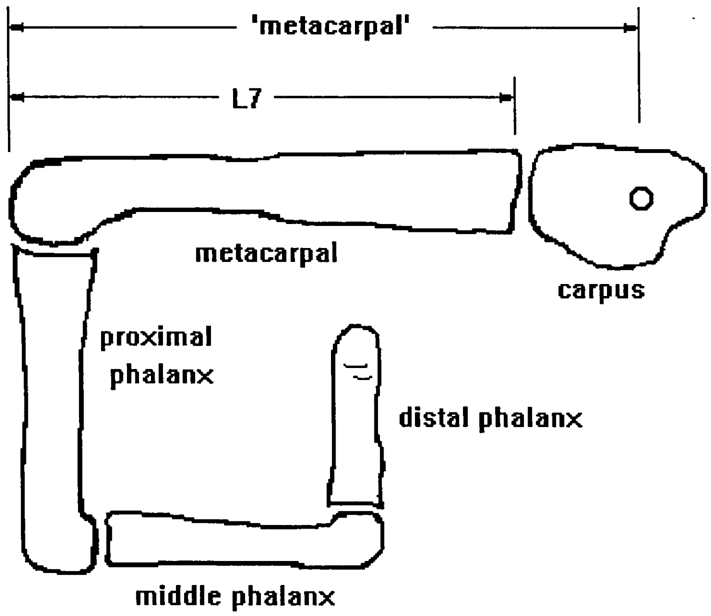


L6: overall length of proximal phalanx
L7: physiological length of the metacarpal
L9: metacarpo-phalangeal joint space

PIP - MCP joint distance = L6 - ((L4-L5)/2) + (0.12*L7) + L9

effective length of proximal phalanx
figure 6.6

Effective length of metacarpal



MCP - Wrist joint distance = (Ri - 0.14) * L7
where Ri is the appropriate ratio described in section 6.1.3, heading (iv).

effective length of metacarpal
figure 6.7

The calculated effective lengths of finger bones, between joint centres, were computed using these formulae and the results are given in table 6.10 (page 178). The ratios of calculated effective lengths of finger bones, between joint centres, were computed and the results are given in table 6.11 (page 179). The mean ratios of effective lengths of adjacent phalanges, with their standard deviation values, are listed in table 6.12 below.

	Index	*Middle*	*Ring*	*Little*
DP/MP	0.811 (0.073)	0.735 (0.046)	0.734 (0.050)	0.928 (0.067)
MP/PP	0.551 (0.050)	0.599 (0.038)	0.605 (0.032)	0.544 (0.057)
PP/MC	0.612 (0.025)	0.675 (0.069)	0.722 (0.042)	0.540 (0.034)

ratios of effective lengths of finger bones between joint centres
table 6.12

6.1.4 Normative models of the four fingers of the hand

Normative models for the fingers were developed in the following manner;

- published data was referred to, to obtain the measured 50th percentile of men's hand lengths, measured from the wrist to the finger tip of the middle finger
- the percentage lengths of the fingers, expressed with respect to the middle finger, were obtained to account for the different finger lengths
- ratios of the effective lengths of finger bones, measured between their joint centres of rotation, were used with the 50th percentiles of published measured values of men's hand lengths to obtain the values of the effective lengths of the phalanges

50th percentile of men's hand lengths:

The 50th percentile of men's hand lengths, measured from the wrist to the finger tip of the middle finger, measured from the dactylions to the stylion (see section 5.4.2.1, page 103), is 191 mm Bailey (1982).

Percentage lengths of the fingers:

The percentage lengths of the fingers, expressed with respect to the length of the middle finger, were obtained by measuring from the dactylions to the stylion (see section 5.4.2.1), from a radiographic textbook (Keats, 1988). These percentage lengths were found to be;

index finger	*middle finger*	*ring finger*	*little finger*
96%	100%	98%	86%

CALCULATED EFFECTIVE LENGTHS OF FINGER BONES BETWEEN JOINT CENTRES

		thumb			index				middle				ring				little			
		dp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc	dp	mp	pp	mc
HAND 1	*right*	23.73			17.98	22.35	43.75	70.44	19.10	28.60	48.64	69.30	18.23	26.35	45.13	61.24	16.73	18.73	36.84	64.51
HAND 2	*right*	24.85			18.98	21.35	41.40	69.58	20.73	26.85	45.26	69.30	19.35	25.60	41.41	58.36	18.10	20.73	35.54	62.84
HAND 3	*right*	22.35			19.10	23.98	43.92	73.89	20.48	27.23	44.73	74.40	20.48	26.60	48.27	64.40	18.35	19.10	33.80	66.50
HAND 4	*left*	20.48			16.85	21.48	38.37	65.26	17.10	24.48	43.13	63.90	16.73	23.23	40.31	55.49	15.23	15.85	32.27	57.86
HAND 5	*left*	22.98			16.60	20.98	41.12	67.28			45.34	65.70	17.73	26.10	41.86	54.91	15.23	17.23	33.96	58.52
HAND 6	*right*	24.98			18.10	23.35	44.16	70.73	19.10	27.98	48.33	69.90	18.98	26.35	45.03	58.36	16.98	18.60	35.29	65.17
HAND 7	*right*	26.23			19.98	24.48	47.57	78.20	20.48	28.48	50.51	78.90	21.10	26.73	47.33	66.99	19.23	18.98	37.72	70.49
HAND 8	*left*	26.10			19.73	23.98	44.56	69.86	20.98	29.48	49.28	70.50	21.35	28.85	45.73	58.94				57.52
HAND 9	*left*	23.85			17.98	20.10	41.47	70.15	18.60	25.60	46.56	72.90	18.10	24.98	42.74	62.10			33.68	64.17
HAND 10	*left*	24.60			19.85	28.48	47.88	75.61	20.98	24.10	43.46	77.40	19.10	23.98	42.59	64.98	17.35	20.85	37.97	70.49
HAND 11	*right*	24.85			17.73	21.73	42.02	71.59	20.35	27.35	46.63	71.40	18.73	26.10	43.74	62.10	16.73	17.60	35.21	66.83
HAND 12	*right*	26.73			18.85	23.60	42.70	71.01	20.10	28.10	47.67	69.60	19.35	25.98	43.89	59.23	18.23	18.60	36.00	64.84
HAND 13	*right*	23.85			18.98	23.60	45.95	76.19	20.10	28.85	50.02	72.60	19.48	26.98	45.96	64.98	18.10	17.98	36.68	66.50
HAND 14	*right*	23.35			18.23	23.35	42.35	75.33			48.39	74.70	18.48	26.85	44.84	62.96			34.41	65.17
HAND 15	*right*				20.23	21.48	40.88	68.43	22.35	27.73	42.36	44.40	20.85	26.98	42.96	59.80	18.23	17.98	34.70	63.18
HAND 16	*left*	26.85			20.73	25.23	46.51	75.61	22.23	30.98	50.84	75.30	20.85	30.23	48.13	63.25	19.60	22.10	39.97	70.49
HAND 17	*left*	25.73			19.98	24.73	43.38	70.44	21.10	28.10	46.49	70.20	19.73	27.73	44.90	60.38	18.60	19.98	35.64	66.17
HAND 18	*left*	26.23			22.23	28.35	46.03	74.75	22.35	29.98	48.93	75.00	21.85	25.48	39.63	63.25	16.73	20.60	37.89	68.50
HAND 19	*right*	26.10			18.48	23.98	47.04	75.90	21.60	29.48	52.60	76.50	20.10	28.10	47.17	68.71	18.23	20.10	38.57	67.83
HAND 20	*left*	25.60			20.23	20.73	38.64	66.41	21.73	29.48	47.93	67.50	18.98	30.10	45.50	56.06	16.73	16.60	34.93	64.17
HAND 21	*left*	23.85			22.35	23.73	45.08	69.00	21.10	28.73	48.51	69.30	19.10	26.35	44.16	58.36	17.60	19.10	34.16	65.17
HAND 22	*right*							72.16				71.70				59.80				65.84
HAND 23	*left*	26.60			22.23	33.10	48.46	72.16	22.23	30.10	44.83	69.90	20.85	29.10	42.26	61.24	20.60	19.85	27.41	67.50
HAND 24	*right*							74.46				75.90				64.98				64.51
HAND 25	*right*	28.85			21.23	27.73	45.72	75.33	23.10	29.60	50.19	76.20	20.35	28.73	47.51	66.41	18.98	22.73	38.47	70.49
HAND 26	*left*							78.78				79.20				67.56				72.49
HAND 27	*left*	28.48			23.98	33.23	49.47	75.33	22.23	33.35	47.25	75.60	22.10	26.60	44.39	66.41	20.48	23.60	37.35	70.49
HAND 28	*right*																			
HAND 29	*left*																			
HAND 30	*right*																			
	SUM	577.18			470.525	585.025	1058.37	1953.85	458.075	624.575	1137.83	1927.2	471.9	644.025	1065.365	1671.2375	375.975	406.85	818.425	1778.21
	MEAN	25.095			19.6052083	24.3760417	44.09875	72.3648148	20.8215909	28.3897727	47.4095833	71.3777778	19.6625	26.834375	44.3902083	61.8976852	17.9035714	19.3738095	35.5836957	65.8596296
	S.D.	1.9315			1.84025015	3.51142916	2.99156032	3.57473781	1.44127703	2.06097034	2.620012	6.64491323	1.35434085	1.71997239	2.3774381	3.79306845	1.4472881	1.96039658	2.61334913	3.83338584

Calculated effective lengths of finger bones between joint centres

table 6.10

RATIO OF EFFECTIVE LENGTHS OF ADJACENT PHALANGES (from table 12)

		thumb		index			middle			ring			little		
		dp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc	dp/mp	mp/pp	pp/mc
HAND 1	*right*			0.80	0.51	0.62	0.67	0.59	0.70	0.69	0.58	0.74	0.89	0.51	0.57
HAND 2	*right*			0.89	0.52	0.59	0.77	0.59	0.65	0.76	0.62	0.71	0.87	0.58	0.57
HAND 3	*right*			0.80	0.55	0.59	0.75	0.61	0.60	0.77	0.55	0.75	0.96	0.57	0.51
HAND 4	*left*			0.78	0.56	0.59	0.70	0.57	0.67	0.72	0.58	0.73	0.96	0.49	0.56
HAND 5	*left*			0.79	0.51	0.61			0.69	0.68	0.62	0.76	0.88	0.51	0.58
HAND 6	*right*			0.78	0.53	0.62	0.68	0.58	0.69	0.72	0.59	0.77	0.91	0.53	0.54
HAND 7	*right*			0.82	0.51	0.61	0.72	0.56	0.64	0.79	0.56	0.71	1.01	0.50	0.54
HAND 8	*left*			0.82	0.54	0.64	0.71	0.60	0.70	0.74	0.63	0.78			
HAND 9	*left*			0.89	0.48	0.59	0.73	0.55	0.64	0.72	0.58	0.69			0.52
HAND 10	*left*			0.70	0.59	0.63	0.87	0.55	0.56	0.80	0.56	0.66	0.83	0.55	0.54
HAND 11	*right*			0.82	0.52	0.59	0.74	0.59	0.65	0.72	0.60	0.70	0.95	0.50	0.53
HAND 12	*right*			0.80	0.55	0.60	0.72	0.59	0.68	0.74	0.59	0.74	0.98	0.52	0.56
HAND 13	*right*			0.80	0.51	0.60	0.70	0.58	0.69	0.72	0.59	0.71	1.01	0.49	0.55
HAND 14	*right*			0.78	0.55	0.56			0.65	0.69	0.60	0.71			0.53
HAND 15	*right*			0.94	0.53	0.60	0.81	0.65	0.95	0.77	0.63	0.72	1.01	0.52	0.55
HAND 16	*left*			0.82	0.54	0.62	0.72	0.61	0.68	0.69	0.63	0.76	0.89	0.55	0.57
HAND 17	*left*			0.81	0.57	0.62	0.75	0.60	0.66	0.71	0.62	0.74	0.93	0.56	0.54
HAND 18	*left*			0.78	0.62	0.62	0.75	0.61	0.65	0.86	0.64	0.63	0.81	0.54	0.55
HAND 19	*right*			0.77	0.51	0.62	0.73	0.56	0.69	0.72	0.60	0.69	0.91	0.52	0.57
HAND 20	*left*			0.98	0.54	0.58	0.74	0.62	0.71	0.63	0.66	0.81	1.01	0.48	0.54
HAND 21	*left*			0.94	0.53	0.65	0.73	0.59	0.70	0.72	0.60	0.76	0.92	0.56	0.52
HAND 22	*right*														
HAND 23	*left*			0.67	0.68	0.67	0.74	0.67	0.64	0.72	0.69	0.69	1.04	0.72	0.41
HAND 24	*right*														
HAND 25	*right*			0.77	0.61	0.61	0.78	0.59	0.66	0.71	0.60	0.72	0.83	0.59	0.55
HAND 26	*left*														
HAND 27	*left*			0.72	0.67	0.66	0.67	0.71	0.62	0.83	0.60	0.67	0.87	0.63	0.53
HAND 28	*right*														
HAND 29	*left*														
HAND 30	*right*														
	SUM			19.4726343	13.2252649	14.6918079	16.1666307	13.1711059	16.1926123	17.6182236	14.5186558	17.3244612	19.486651	11.4186118	12.4111787
	MEAN			0.81135976	0.5510527	0.61215866	0.73484685	0.59868663	0.67469218	0.73409265	0.60494399	0.72185255	0.92793576	0.54374342	0.53961646
	S.D.			0.07323697	0.05037546	0.02535743	0.04569667	0.03778084	0.06886129	0.05000214	0.03177309	0.0419578	0.06637505	0.05652912	0.03415569

Ratio of effective lengths of adjacent phalanges
table 6.11

Effective lengths of finger bones:

The effective lengths of individual phalanges were calculated for the 50th percentile of a man's hand length, using the appropriate ratios given in table 6.12 (page 177). For example, the index finger's distal phalangeal length of 22.52 mm can be calculated from the expression;

$$DP \{ 1 + 1/(0.811) + 1/(0.811*0.551) + 1/(0.811*0.551*0.612) \} = 0.96*191$$
$$DP = 22.52$$

The calculated effective lengths of all the phalanges are:

	DP	*MP*	*PP*	*MC*	*TOTAL*
index finger	22.52	27.76	50.39	82.33	183
middle finger	23.88	32.50	54.25	80.37	191
ring finger	24.97	33.84	52.79	76.40	188
little finger	21.23	22.87	42.04	77.86	164

effective lengths of all phalanges
table 6.12A

These were the values used for the manufacture of the finger linkage (section 5.5.3) and for the analysis of its kinematic performance (section 5.5.4).

6.2 Recovery of hand function following surgery

Section 5.2 described the development of equipment for measuring and recording hand strength. This equipment was used to measure the recovery of hand function of patients who had been operated upon for Dupuytren's contracture, in order to determine the period for which time hand strength is adversely affected. This would provide an indication of how long a CPM machine should be applied. This section provides a description of the Dupuytrens control group, the test protocol which was followed to obtain baseline data, the results of tests upon the control group, and an interpretation of the results.

6.2.1 Control group and test protocol

The control group comprised of patients with Dupuytren's disease. A total of 48 hands were tested in the group which included four patients with bilateral conditions. Ninety per cent of the patients were right hand dominant and their right hands accounted for the majority of the affected hands. Ninety four per cent of the patients were male (table 6.13) and their ages were concentrated in the 60-69 age group (table 6.14).

Sex distribution:

Age	*Number of patients*	*Relative frequency*
Female	3	6
Male	46	94
Total	49	100

Sex distribution of Dupuytrens patients
table 6.13

Age distribution:

Age	*Number of patients*	*Relative frequency*
Under 50	6	12
50 to 59	9	18
60 to 69	23	47
70 and above	11	23
Total	49	100

Age distribution of Dupuytrens patients
table 6.14

Each patient had the same operative technique (the McCash open palm procedure), was operated upon by the same surgeon and had the same post-operative management regime (namely bandaging for two weeks within a static WHO). One person, an occupational therapist, conducted all their assessment procedures. By adopting this strict regime, extraneous variations in data attributable to factors other than physiological recovery, were eliminated as much as possible. A strict test protocol was followed on each occasion. Before testing commenced, the therapist explained the purpose of each test and ensured that the subject was comfortably seated and relaxed. A check was made that the subject understood what was required of him and that the transducer was comfortably located in his hand. Patients were given fourteen tests, seven for each hand. These were tip pinch (index finger only), lateral pinch, finger grasp (digits 2 and 5) and skin shear. The pinch/grasp transducer had an integral knob, which could be used to adjust the distance between the finger and thumb plates to accommodate hands of varying sizes, or hands with finger joint contractures. In general however, a gap of two centimetres was used between the finger and thumb and the plates were removed when the transducer was used for the measurement of grasp. The skin shear transducer was positioned between a heavy weight and a smooth cylinder. The patient attempted to lift the weight in a vertical direction and the test measured the shear force between the palmar surface of the patient's fingers and the cylinder, at the point of slipping.

In a preliminary trial, it was found that repetitive tests of hand strength, undertaken without rest, showed deterioration in pinch and grasp forces because of fatigue. In order to compensate for this problem, it was decided that if, for any reason, a test was deemed unsatisfactory, it would not be repeated until after three minutes rest. It was also observed that patients could learn to 'snatch' the force transducers in order to achieve a higher force value with rapid muscle contraction, than could be achieved with a gradually contracted muscle. In order to overcome this distortion of data, the test protocol required the patients to exert maximum force before the start of the data-recording programme. Eighty-one force values of a particular test (pinch, grasp, etc) were recorded during a four second period. These values were then divided into nine equal samples and the average of the maximum values in each sample was then computed. This method evened out fluctuations.

Finally, the test protocol included measurement of maximum extension angles for each finger joint (i.e. the joint contraction angles) using small protractors. At all stages, the operator acted in accordance with prompts displayed on the monitor, which listed the procedures to be followed in each test. The therapists had no difficulty operating the equipment after initial familiarisation. Similarly, patients had no difficulty in understanding or performing tests. Patients were tested immediately prior to surgery, then in the intervals between the 2nd and 4th week post-surgery when all bandages were removed, and also in the intervals between 4th and 6th weeks, 6th and 8th weeks, 8th and 10th weeks.

At the completion of the trial, which was conducted completely 'blind', with no on-going analysis of results, data files were formed comprising 5405 data elements. The data for the non-operated hands is listed in appendix 4, table A4-1; the data for the operated hands, obtained prior to surgery and at the post-operative periods (between the 2nd and 4th weeks, 4th and 6th weeks, 6th and 8th weeks, and 8th week onwards) is listed in appendix 4, table A4-2.

6.2.2 Process of data

The SPSS statistical computer package was used for the analysis. Missing data was prescribed the value '-1' and was subsequently ignored. The minimum, maximum, range and mean values of data were computed, together with standard error, standard deviation, skewness[1] and kurtosis[2] (both defined below) for each of the fourteen tests (tip pinch, lateral pinch, finger grasp for the four digits and skin shear). The results are shown in tabular form in appendix 4, tables A4-3 to A4-9, and in graphical form in figures A4.1 to A4.14. The results for the maximum extension angles of the individual MCP, PIP and DIP joints are shown in tabular form in appendix 4, tables A4-10 to A4-20, and in graphical form in appendix 4, figures A4.15 to A4.36. Finally, the sum of the maximum extension angles of the MCP, PIP and DIP joints for each finger are shown in tabular form in appendix 4, tables A4-21 to A4-24, and in graphical form in appendix 4, figures A4.37 to A4.44.

The equipment's repeatability was determined by noting the monitor values of particular forces applied to each transducer at one minute intervals over a period of nine minutes. Coefficients of variation (standard deviation of force magnitudes x 100/mean) ranged between 0.148% and 1.746% for the pinch/grasp transducer and between 0.066 and 3.5% for the skin shear transducer. These low coefficients of variation indicate the spread of results of subjects' tests could be attributed to the changing conditions of the patients themselves.

[1] Skewness of data about its mean is a test to compare the frequency distribution of the data about its mean value with a normal frequency distribution.

[2] Kurtosis is a measure of the so-called sharpness, or peakness of data. A null value of kurtosis is equivalent to a normal distribution. Positive values represent excessive clustering of data about a mean; negative values represent scarcity of data about the mean.

6.2.3 Results

The incomplete attendance record of patients in the control group (regrettably a common problem in clinically based studies) can distort the statistical results of a clinical trial so care was exercised when interpreting the data. Table A4-25 shows the attendance record of the forty eight patients, superimposed on the data for the sum of the finger joint angles at different stages in the clinical trial. Attendance is illustrated by darkened cells and non-attendance by clear cells. The numerical values indicate the sum of the maximum extension angles of the MCP, PIP and DIP joints (i.e. the joint contracture angles) for the ring and little fingers and therefore can be used as a guide to the severity of the finger deformities. In this study, it was decided that interpretation of the results would be best provided by considering the data in three time periods, in order to minimise distortion of the data. Accordingly, the data was grouped into the following three sets;

- *FIRST SET: pre-surgery and 2-4 weeks post-surgery*
  five patients (5, 16, 17, 28, 40) were lost in the first follow-up but by keeping them in the pre-surgery set, a fuller interpretation could be made of the original condition

- *SECOND SET: 4-6 weeks & 6-8 weeks post-surgery*
  Six patients (4, 9, 32, 35, 42 and 43) from the remaining forty-three patients failed to attend for any further reviews and the remaining thirty-seven patients comprised this second group. Of these, twenty-two (2, 3, 7, 10, 13, 14, 18, 20, 21, 22, 23, 25, 26, 29, 30, 31, 33, 34, 36, 38, 44, 45) attended both of the two reviews in the 4-6 weeks & 6-8 weeks post-surgery periods, and fifteen (1, 6, 8, 11, 12, 15, 19, 24, 27, 37, 39, 41, 46, 47, 48) attended only one.

- *THIRD SET: 8+ weeks post-surgery*
  This set comprised only ten patients of which four (12, 14, 22, 34) had severe contractures and did not attain any further increase in joint range of motion, and the remaining six patients (18, 20, 23, 25, 30, 33, 45) made good recoveries and attended the reviews primarily at the request of the researchers.

6.2.3.1 Recovery and return of strength

The first stage of the analysis investigated the recovery and return of strength. Not surprisingly, the mean values of tip & lateral pinch, individual finger grasp and skin shear all diminished whilst the patients' hands were immobilised in plaster *(set 1)*, and all showed gradual and approximately linear recovery in the 2-8 week post-surgery period *(sets 1 and 2)*. The mean grasp strength of those patients never attained its original value. Tip pinch recovery showed a very similar pattern to finger grasp strength although the changes in lateral pinch, which relies upon the abduction of the index finger, showed a sharper gradient in the return of strength. The most pronounced recovery was in the skin shear test, an activity which involved the entire hand for which patients experienced within 6% a full recovery of mean strength *(set 3)*.

Tests were performed to determine to what extent the collected data had a normal frequency distribution about its mean value by calculating its standard deviation and standard error, as well as the skewness of data about its mean and the value of its kurtosis. The strength data had similar patterns, namely the greatest standard deviation occurred *before* surgery but the greatest skewness and kurtosis occurred *after* bandages were removed at the 2 - 4 week assessment period (with the exception of the 'problem cases' seen at the 8 + week review). Skewness and kurtosis were less marked in ring finger grasp but because of similarity of results, the general conclusion was drawn that tests performed at the time of the removal of bandages indicate that data collected at this occasion is less predictable in its value than at other occasions.

6.2.3.2 Recovery and return of finger joint extension angle

The second stage of the analysis investigated the reduction in the finger joint contraction angles. The mean results for the ring and little fingers, obtained at the surgical table, were retained in the post-operative periods. The magnitudes of the standard deviation of joint angles was greatest before surgery, demonstrating the diversity of the deformities. Kurtosis was noticeably high for the ring fingers' MCP joints, both pre-surgery and at the 4 - 6 week period *(set 2)*, as well as for the DIP joints at all stages post-operatively. Similarly, high kurtosis values were obtained for the little fingers' DIP joints. However, patterns and trends could not be identified and plots of standard errors, skewness and kurtosis showed puzzling variations, which were thought to be attributable to practical difficulties in measuring joint angles accurately and independently. For these reasons, it was decided to analyse the combined angle of the MCP, PIP and DIP joints for the ring and little fingers.

The results, illustrated in figures A4.37 to A4.44 in appendix 4, were unexpectedly rewarding. The trends in all computed parameters (i.e. maximum, mean and minimum values; standard deviation and error, skewness and kurtosis) were all remarkably stable in the post-surgery periods *(sets 2 and 3)*, even after accounting for clinical regression and progression in individual patients. The changes, which did occur in these parameters, took place in the period between surgery and the first post-operative assessment.

6.2.3.3 Conclusions and their effect upon design and use of hand CPM machines

The following conclusions were drawn from the results of the patient assessments. Hand strength diminished during the period the hand was bandaged but recovered when the bandages were removed. The tests showed that pinch (tip and lateral) recovered more quickly than ring and little finger grasp. Even the grasp strength of the index finger, a digit rarely affected by Dupuytren's disease, showed a sudden deterioration followed by a progressive improvement throughout the recovery period. Tip pinch recovery showed a very similar pattern to finger grasp strength although the improvement in lateral pinch, which relies upon the abduction of the index finger, showed a sharper gradient in the return of strength than the tip pinch. It is significant that the recovery of hand strength (grasp in particular) continues during the *entire* eight week post-surgery period. It is reasonable to presume that, if clinically permissible, CPM should be applied as soon as possible and continued for eight weeks.

6.3 Application of the twin-actuator CPM machine - Berlin data collection

6.3.1 Aim

The twin actuator CPM machine was applied to patients in Oskar-Helene-Heim's occupational therapy department to determine the clinical effectiveness of hand CPM. The assessments were made in two ways, firstly through measurements in before-and-after changes in finger joint angles (active movement only) and secondly through measurements in the reduction in force applied by the machine to move stiffened finger joints, in order to gauge the reduction in finger joint stiffness. It was impractical to include hand strength tests because this would take too long in the busy clinic. Furthermore, the previous hand strength tests had been performed exclusively on patients with Dupuytrens contractures whereas the Berlin patients had a variety of hand conditions. Comparisons between the Dupuytrens and Berlin patients would have been inappropriate.

6.3.2 Method

6.3.2.1 Selection and diagnoses of patients

Clinical practitioners selected eighteen patients for assessment and testing was performed by occupational therapists in the hospital. Details of the patients' diagnoses and treatments are shown in table 6.15 overleaf.

6.3.2.2 Test protocol

The CPM machine was fitted to each patient using the modular orthoses developed in Dundee. The machine was carefully positioned in order that its support platform so that the actuating rods passed over the scaphoid so that the fingers were flexed & extended in their natural arcs of movement. The therapists decided the most appropriate type of finger splint to use, to fit the actuator rods to the fingers. Typically the hinged plates on the distal ends of the rods were taped directly to the pulps on the distal phalanges but if these were inaccessible, customised orthoses were fabricated. Each patient test normally lasted one hour but the decision for this period was entirely arbitrary.

	PATIENT	d.o.b.	OCCUPATION	DIAGNOSIS AND TREATMENT	AFFECTED DIGITS & HAND
1	RB	eighty years old approx	retired	Wrist fracture followed by Sudeck contracture.	all joints - right
2	MW		student		dig 5 dip - right
3	MK	28/12/39	barman	Bicycle accident (12 April 1992) when he sustained a palmar cut injury in the skin crease of the PIP joint of the right ring finger. He had primary surgery, on the day of the accident, to clean the wound and for skin sutures. No damage to the tendons was seen. He subsequently suffered post-traumatic limitation in movement of the DIP joint. Two months after the accident (15 June 1992), arthrolysis of the DIP joint was performed and CPM treatment commenced on 6 July 1992. Ideal patient for CPM because after arthrolysis because there is no possibility of further damage.	dig 4 pip - right
4	GZ			Smith fracture followed by Sudeck contracture.	dig 3 pip -right
5	CDB	20/8/72		Hand was crushed in the U-bahn underground train on 30 November 1991. Patient had a severe contusion of the right hand with open fracture of the proximal phalanges of the index and ring fingers, the middle phalanx of the ring finger and the distal phalanges of the ring and little fingers. Wire osteosynthesis undertaken on the day of the injury. Arthrodesis of the little finger DIP and arthrolysis of the ring and little finger PIPs undertaken on 7 July 1992. Kirchner wire removed from little finger MCP and tendolysis of ring finger PIP performed on 1 February 1993. Kirschner wires removed from little finger and un-united fracture bone in ring finger replaced with fresh bone on 11 March 1992. CPM treatment commenced on 19 August 1992.	dig 4 pip - right

Patients' diagnoses and treatments – Berlin
table 6.15 (sheet 1 of 3)

6	AM	4/9/63	machine operator	Traumatic lesion of the flexor tendons to the middle, ring and little fingers in the areas of the proximal phalanges. Primary tendon repair performed on the day of injury, 10 November 1991, followed by Kleinert traction therapy. Tendolyses on the flexor tendons of the middle, ring and little fingers and an arthrolysis of the little finger DIP were performed on 22 January 1992 to relieve flexion contractures. Hard tissue scars remained on the palmar surfaces of the injured fingers in the region of the injuries on the proximal phalanges. CPM treatment commenced on 15 May 1992.	digs 3, 4 and 5 pip - right
7	CM	12/6/51	child minder	Attempted to commit suicide on 15 April 1991 when she cut herself on the left wrist and left elbow. She had complete lesions of all superficial and deep tendons, the ulnar & median nerves, as well as the arteria ulnaris. Nerves (from the foot) were transplanted into the hand on 18 October 1991. Neurolyses of the median & ulnar nerves and tendolyses of all deep tendons and the flexor pollicis longus were performed on 26 August 1992. CPM treatment began on & September 1992.	digs 4 & 5 pip - left
8	IS				digs 2 & 3 mcp - left
9	GE				digs 2 & 4 pip - right
10	RV			Crush injury but no fracture to the index finger of the left hand on 4 March 1993. After the injury had healed, there was a lack of movement of the PIP and DIP joints. No operation was performed. At the time of CPM treatment, the finger was swollen, the skin a little red and sensibility was a little diminished.	dig 2 pip and dip - left
11	TS				dig 5 pip - right
12	EP				dig 5 pip - left
13	Ma				digs 2 & 5 pip - left

Patients' diagnoses and treatments - Berlin

table 6.15 (sheet 2 of 3)

14	Ha				digs 2 & 3 pip - left
15	ML			Torn fibrocartilage of the left little finger PIP joint	dig 5 pip - left
16	Ka			Osteomylitis resulting in synovectomy of the right elbow. The elbow was held in a fixed flexed position but this resulted in flexion contractures of the 4th and 5th fingers. The finger contractures were secondary problems to the elbow problem.	
17	Jo				
18	Wi		doorman	Patient had a Dupuytren's contracture which became progressively worse over an eighteen month period. His left little finger was amputated and a palmar fascia excision was performed in December 1991. CPM treatment commenced after the operation, to exercise the MCP joints of the middle and ring fingers; the PIP joints were fixed and the DIP joints were free. The patient had a partial aponeurectomy performed on 6 May 1993.	

Patients' diagnoses and treatments - Berlin
table 6.15 (sheet 3 of 3)

Details of the number of visits for the twelve patients who attended for assessments of the changes in finger joint angles, pre & post CPM, are illustrated in table 6.16. The details of the number of visits for the fifteen patients who attended for assessments of the changes in CPM force application, pre & post CPM, are illustrated in table 6.17. Inevitably some data was missing because testing was done in a busy clinical environment and not in an artificial laboratory setting.

6.3.2.2 - (i) Patient visits for assessments of changes in finger joint angles; Pre & post CPM

Twelve of the eighteen patients were assessed for changes in joint angles and ranges of motion. These patients had a total of 275 visits, listed in table 6.16.

	PATIENT	*AFFECTED DIGITS & HAND*	*NUMBER OF VISITS DURING WHICH CHANGES IN JOINT ANGLE WERE RECORDED*
1	RB	all joints - right	39
2	MW	dig 5 dip - right	
3	MK	dig 4 pip - right	10
4	GZ	dig 3 pip -right	11
5	CDB	dig 4 pip - right	20
6	AM	digs 3 & 4 pip - right	25
7	CM	digs 4 & 5 pip - left	15
8	IS	digs 2 & 3 mcp - left	
9	GE	digs 2 & 4 pip - right	
10	RV	dig 2 pip - left	
11	TS	dig 5 pip - right	
12	EP	dig 5 pip - left	
13	Ma	digs 2 & 5 pip - left	31
14	Ha	digs 2 & 3 pip - left	39
15	ML	dig 5 pip - left	22
16	Ka		31
17	Jo		4
18	Wi		28
			TOTAL: 275

Number of visits to assess changes in finger joint angles, pre & post CPM
table 6.16

6.3.2.2 - (ii) Patient visits for assessments of changes in CPM force application; pre & post CPM

Fifteen of the eighteen patients had records taken of force data. A total of 128 hours of data was recorded, for which a summary is provided in table 6.17 below. The data for eleven patients (78 hours), highlighted in bold below, was reviewed in detail.

	patient	minutes of data recorded in each treatment session									minutes / hours of recorded data
1	RB	10 49 28 15 9	19 15 5 9 54	11 12 13 30 69	8 34 26 54	8 70 21 6	10 13 21 5	16 28 18 39	12 38 26 59	6 26 24 36	952 / 15.87
2	MW	2 15 20	36 13 18	39 14 15	50 15 21	20 21 24	15 10	13 20	19 10	20 20	450 / 7.50
3	**MK**	30	45	49	4						128 / 2.13
4	**GZ**	47	52	53	50	50	64	55	35		406 / 6.77
5	**CDB**	51	43	42	49	43	53				281 / 4.68
6	**AM**	23 48	20 37	46 50	54 31	52 39	42 41	53 32	56 40	38 39	741 / 12.35
7	**CM**	31 34	25 31	33 27	34 32	35 40	29 39	32 47	27 37	23 38	594 / 9.9
8	**IS**	46 15 34	45 45 45	45 36 20	45 45 41	45 45 44	35 18 28	44 39	45 6	39 40	890 / 15.63
9	**GE**	7 24	45 4	44	46	17	11	24	65	20	307 / 5.12
10	**RV**	32	40	20	42	22	15	58	46		275 / 4.58
11	TS	50 52 20 21 25	57 60 23 27 50	61 26 28 23 52	58 48 23 19 20	58 52 28 27 24	44 53 5 28 21	51 40 20 22 15	41 28 29 23 46	10 20 31 26	1485 / 24.75
12	**EP**	56	58	15	58						187 / 3.12
13	**Ma**	56	11	5	56	54	65	65	53	24	389 / 6.47
14	**Ha**	27	58	56	46	61	54	32	56	46	436 / 7.27
15	ML	46	58								110 / 1.73
16	Ka										
17	Jo										
18	Wi										
											TOTAL: 128 hrs

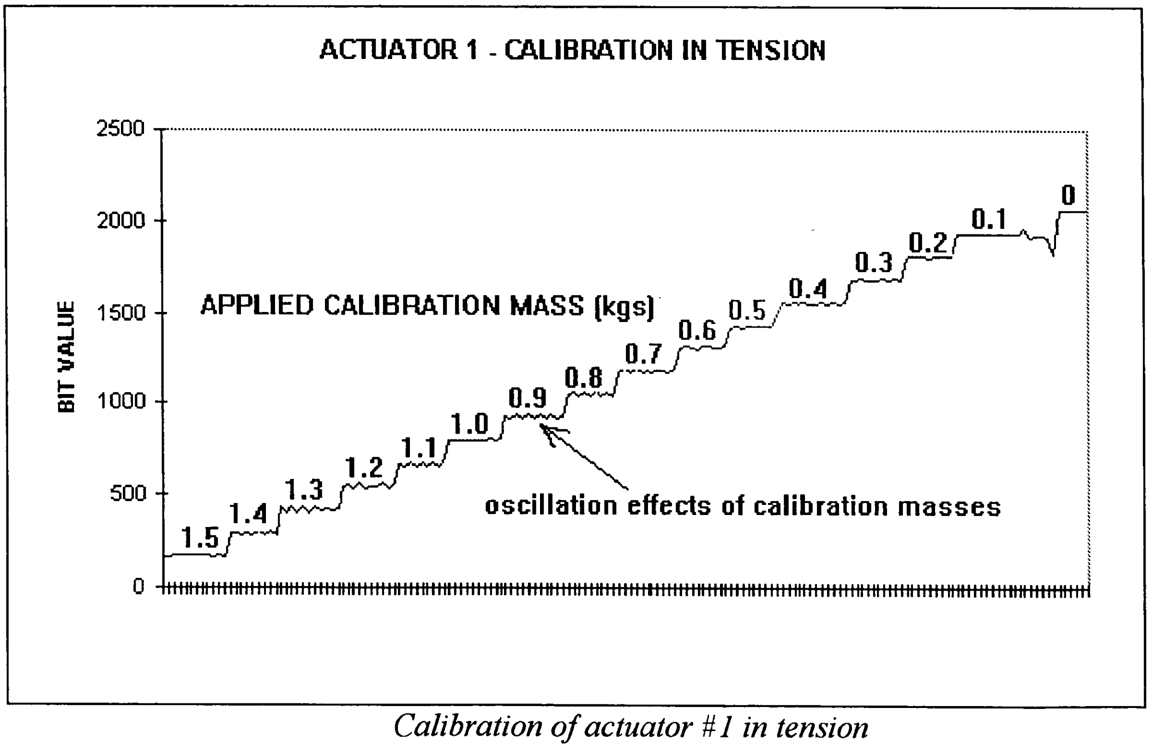
Number of visits to assess changes in CPM force application, pre & post CPM
table 6.17

6.3.2.3 Calibration of the force and position transducers

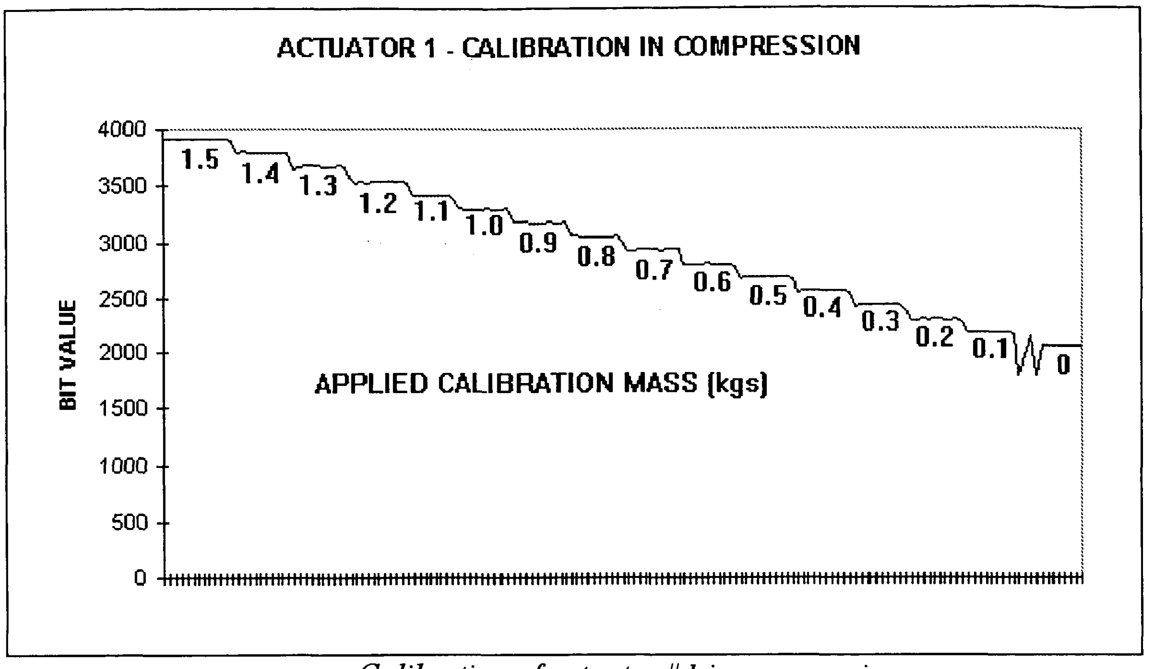
(i) Force transducers

The two strain gauged force transducers were calibrated independently of one another and a check made that there was no cross-talk. Calibration was performed in a frame which was used to alternatively load the transducers in ompression and tension. The transducers were loaded in increments of 100 gm and the amplified signal data was continuously recorded. The data was slightly affected by the oscillation of the applied calibration masses, so it was smoothed by averaging the output bit values for each load.

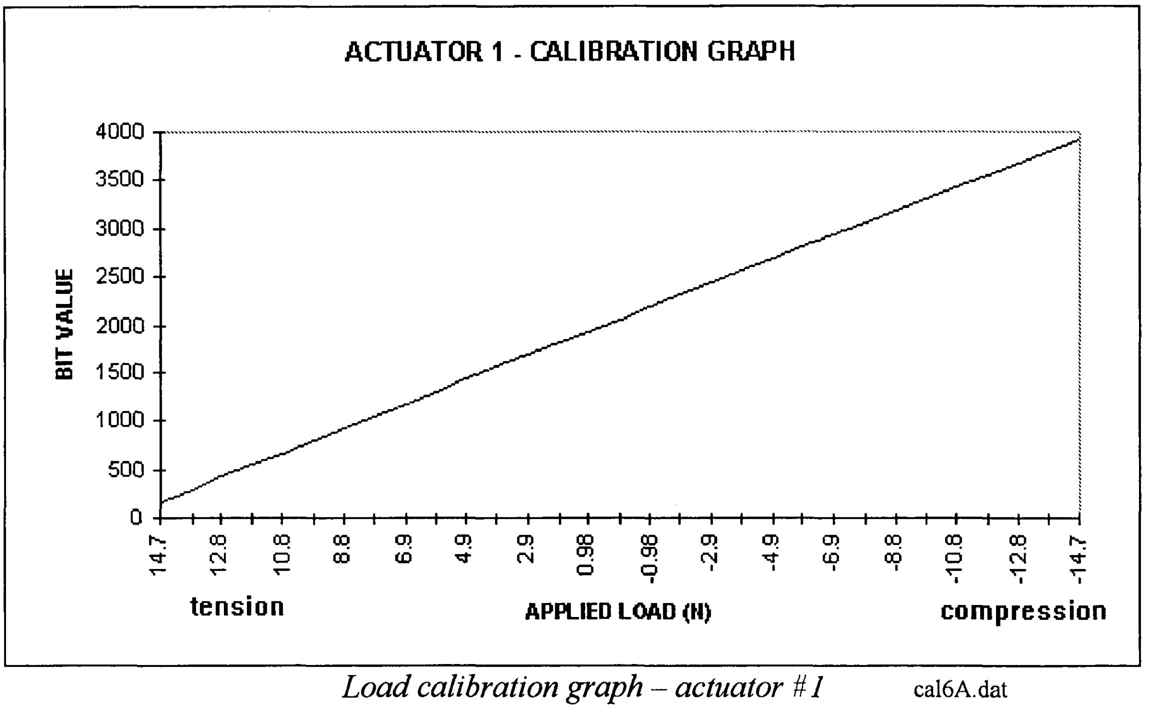
The lower actuator, when the cover was removed, was numbered actuator one; the upper actuator was actuator two. The results of the calibration load tests on actuator 1 are shown in figures 6.8 and 6.9. The oscillation of the masses in the calibration frame caused small fluctuations in the reaction force provided by the transducer, with a corresponding fluctuating bit value especially for the greater masses. These bit values were averaged before they were used for the calibration graph and there was some concern that this averaging might distort the calibration equation. In fact, the correlation coefficients were excellent and the concern was unfounded. The calibration graphs is shown in figure 6.10 (page 194) and figure 6.13 (page 196).



Calibration of actuator #1 in tension
figure 6.8



Calibration of actuator #1 in compression
figure 6.9



Load calibration graph – actuator #1 cal6A.dat
figure 6.10

Applying linear regression for fitting the data to a straight line;

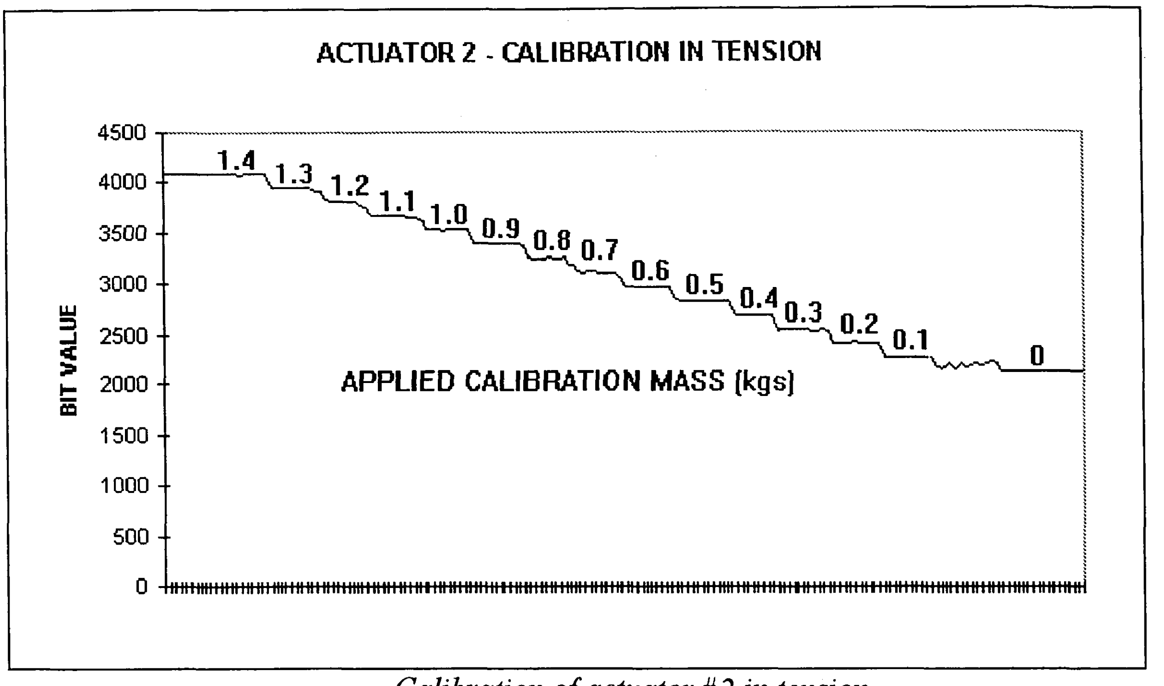
$y = mx + c$ *y = bit value; x = applied load (N)*

where $m = -127.44$ and $c = 2051.29$

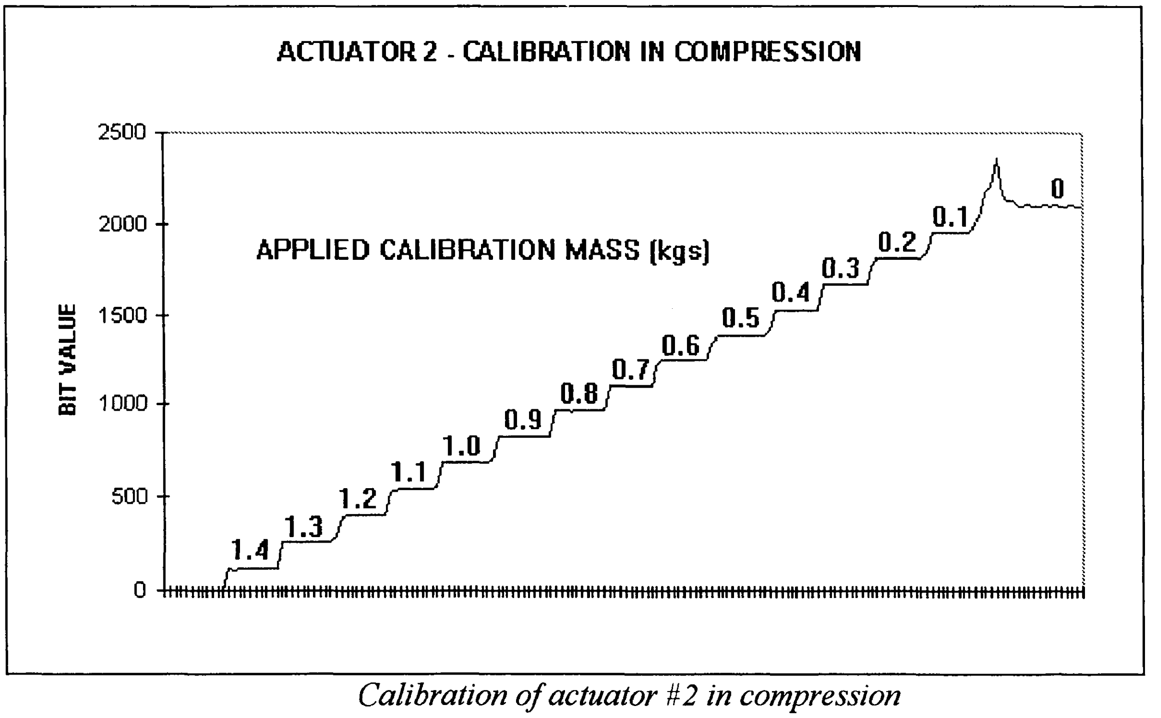
Hence; $y = -127.44x + 2051.29$

The results of the load tests on actuator 2 are shown in figures 6.11 and 6.12.

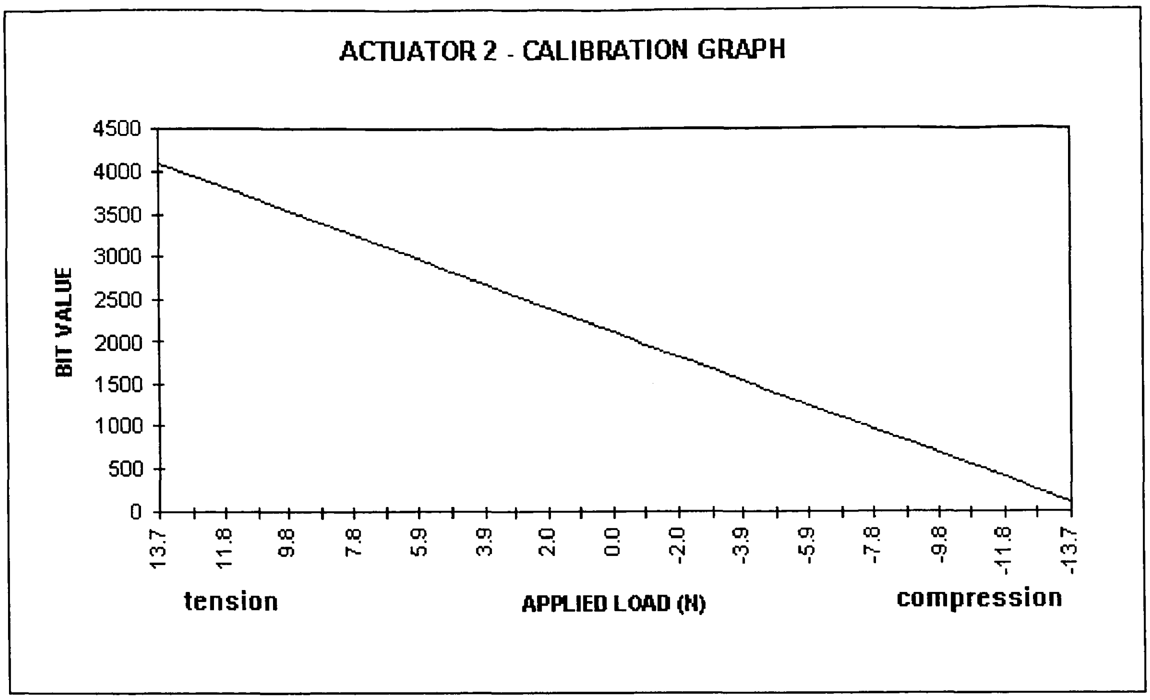
The calibration graph is shown in figure 6.13.



Calibration of actuator #2 in tension
figure 6.11



Calibration of actuator #2 in compression
figure 6.12



Load calibration graph – actuator #2 cal7B.dat

figure 6.13

Applying linear regression for fitting the data to a straight line;

y = mx + c *where* m = 145.27 *and* c = 2109.86

and y = bit value *and* x = applied load (N - tension is positive)

Hence; y = 145.27x + 2109.86

(ii) Position transducers

The strokes of actuators 1 and 2 were 79 and 82 millimetres respectively. Their position transducers were calibrated and linear regression applied to the data to obtain the best straight line fit for the data. The results are listed in tables 6.18 and 6.19 below.

actuator 1 ***(data file: CALLIN1.DAT)***	***actuator 2*** ***(data file: CALLIN2.DAT)***
y = mx + c	y = mx + c
where m = -7.79 *and* c = 3568.16	*where* m = -7.97 *and* c = 3565.73
and y = bit value *and* x = displacement	*and* y = bit value *and* x = displacement
hence y = -7.79x + 3568.16	*hence* y = -7.97x + 3565.73

Potentiometer calibration – actuator #1 table 6.18

Potentiometer calibration – actuator #2 table 6.19

The best-line fits for the actuators' force and position transducers were used to provide the data listed in appendix 5.5

6.3.2.4 Data Collection

6.3.2.4 - (i) Joint Angle Data

Changes in finger joint angles were recorded, using the European neutral-flexion-extension method, onto forms used by the occupational therapists in their routine clinical work. The original un-processed data (which was considerable) was manually transferred to a customised Excel™ spreadsheet, which is shown in appendix 5.1 *(Original data - active ranges in finger joint angles; pre- and post- CPM treatment).*

6.3.2.4 - (ii) Force and Actuator Position Data

Force and actuator position data were recorded, using a standard PC and 12-bit interface card (Amplicon PC26A), at a rate of 2.0126 lines of data per second (two force signals and two position signals). The total size of data were 35.5 megabytes (calculated on the basis of 7,660 bytes of data per minute, equivalent to 559,583 lines of data) and it was compressed in Berlin for analysis in Dundee.

6.3.3 Process of Data

6.3.3.1 Changes in finger joint angles

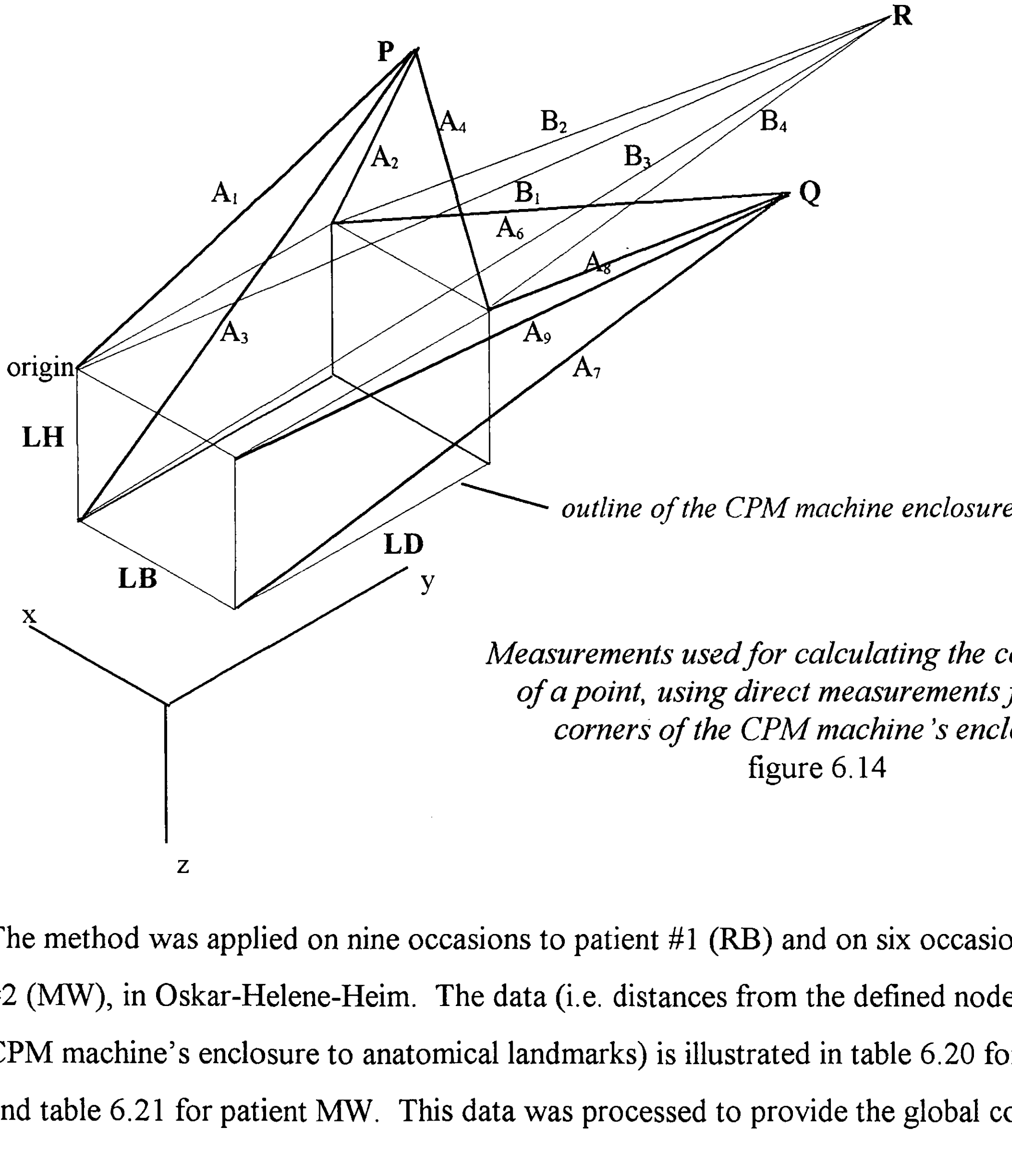
The spreadsheet data of joint angle data was processed to provide plots of changes in maximum joint extension angle or maximum joint flexion angle (as appropriate) and the joint range of movement. The latter was necessary to check that the treatment did not merely 'shift' the range of movement. The changes in finger joint angles are shown in appendix 5.2, *(Plots of the changes in patients' finger joint angles; pre- and post- each CPM treatment session).* The effect of **each** CPM treatment session on finger joint angles is shown in appendix 5.3, *(Details of the percentage occurrences of changes in patients' finger joint angles, provided by each CPM treatment session)*. This provides a summary of the number of occurrences, when changes were achieved in finger joint maximum flexion or extension angle (as appropriate) and in joint range of movement, during each CPM treatment session. The data are expressed in five degree increments for each patient. The effect of **all** CPM treatment sessions on finger joint angles is shown in appendix 5.4, *(Mean and standard deviation values* *for the maximum and minimum finger joint angles, recorded before and after each CPM treatment session, for the entire treatment period of each patient).*

6.3.3.2 Force and actuator position data

The quantity of force and actuator position data (35.5 megabytes) was so large that difficulties were encountered in identifying a suitable method of reducing and processing it. The was finally decided to use a software package, *Turboview for Windows (ver 3.23)* which had in-built facilities for calculating maximum, minimum, mean values, standard deviations and fast fourier transforms, features which were all used in the data analysis. Although other methods such as neural network analysis were considered, it was decided that the likely results from using the first approach outweighed the enormous effort required to develop a satisfactory model. Accordingly, the force & position data were analysed by the rather laborious (though ultimately faster) method of manually transferring individual sections of data into the *Turbo-view* analysis package. The force and position data were reduced by investigating each complete period of actuator movement as separate sub-sets of data between the periods of actuator rest. Each sub-set of data was referred to as a 'period of cycle' and was interrogated for minimum, maximum, mean, standard deviation and percentage of data above the mean value. The results are listed in appendix 5.5, *(Summary of actuator force and position data).*

6.4 Calculation of spatial data for the rigid body segments in a hand using direct measurements - Berlin data collection

The reason for inserting the electro-mechanical goniometers within the finger linkage (previously described in section 5.7) was to obtain spatial data of the movement of a finger in a particular CPM treatment session. This spatial data could be coupled with force data in order to calculate the corrective moments exerted by a CPM machine about individual finger joints. However, the insertion of the electro-mechanical goniometers within the linkage (and their subsequent protection against accidental mechanical damage), was a difficult and time-consuming task. Before the linkage was completed, it was decided to investigate alternative method of obtaining spatial data for the movement of the rigid body segments in a hand. Optical methods were discounted because they would be impractical in a busy occupational therapy department. Instead, a study was made to investigate the possibilities for making direct measurements when the finger was in its fully flexed and extended positions, in order to obtain spatial data necessary for moment calculations. The method required direct measurements to be taken from four corners of the CPM machine to each particular point on the skin, in order to define the coordinates of that point in a 'global' axis system. This global axis system coincided with the edges of the CPM machine and its origin was located at one of its corners (figure 6.14 below). The global coordinates of the wrist's flexion/extension axis on the radial and ulnar skin surfaces (shown as points *P* and *Q* in the figure below), as well as the coordinates of points on the dorsal skin surfaces immediately above the MCP, PIP and DIP (illustrated with one point *R* in the figure below) were computed. The procedure for determining the coordinates of a point, using direct measurements from nodes, is described in appendix 2, as well as the relevant calculations. The programme listing is shown in appendix 3.1.



Measurements used for calculating the coordinates of a point, using direct measurements from the corners of the CPM machine's enclosure
figure 6.14

The method was applied on nine occasions to patient #1 (RB) and on six occasions to patient #2 (MW), in Oskar-Helene-Heim. The data (i.e. distances from the defined nodes on the CPM machine's enclosure to anatomical landmarks) is illustrated in table 6.20 for patient RB, and table 6.21 for patient MW. This data was processed to provide the global coordinates of the wrist's flexion/extension axis on the radial and ulnar skin surfaces, as well as a point on the dorsal surface of the metacarpal joint for a finger being subjected to CPM. These results are given in tables 6.22 for RB, and 6.24 for MW. The rotation of the wrist axis with respect to the 'global' coordinate axis system was calculated and the results are given in table 6.23 for patient RB, and table 6.25 for patient MW.

Test No	A1	A2	A3	A4	A6	A7	A8	A9	B1	B2	B3	B4
1	21.2	11.8	17.7	13.4	12.7	17.7	13.7	20.4	27.5	16.7	25.5	16.2
2	25.6	14.6	21.8	15.5	14.5	20.2	14.1	23.5	29.4	16.7	27.1	15.6
3	24.3	13.6	21.2	14.6	11.4	20.7	12.0	23.5	31.2	17.6	27.8	17.5
4	25.1	13.9	22.5	15.6	13.4	21.4	13.7	23.4	25.2	17.2	27.3	18.1
5	25.0	13.0	22.4	15.0	12.5	19.7	12.4	22.4	32.6	16.9	29.0	17.1
6	25.4	14.0	22.8	16.2	12.8	20.5	12.0	22.8	30.5	17.6	28.2	17.6
7	26.6	14.5	22.7	16.0	13.6	21.6	12.7	24.1	31.7	18.1	29.3	18.0
8	28.1	15.7	25.8	17.1	13.8	24.5	14.1	25.3	32.7	19.8	31.0	19.3
9	27.7	14.9	25.0	16.6	12.8	22.9	12.7	25.4	32.8	19.6	30.8	18.7

Distances from the defined nodes on the CPM machine's enclosure to anatomical landmarks - patient RB

table 6.20

Test No	A1	A2	A3	A4	A6	A7	A8	A9	B1	B2	B3	B4
1	22.1	11.5	21.1	12.0	12.4	19.9	9.4	20.8	29.0	14.7	27.7	15.8
2	26.7	14.1	24.4	17.0	14.3	22.2	13.5	25.8	32.0	19.4	29.2	18.8
3	23.6	13.2	20.4	14.8	13.8	19.5	13.3	22.2	29.4	16.4	26.6	17.3
4	24.5	14.1	20.9	14.8	14.1	19.6	13.3	22.4	29.6	16.7	27.1	17.6
5	24.2	15.5	21.7	16.1	13.7	20.7	13.5	23.5	30.7	14.1	28.4	13.3
6	22.0	13.4	19.6	15.1	13.7	17.7	12.2	21.5	28.7	16.2	25.9	16.7

Distances from the defined nodes on the CPM machine's enclosure to anatomical landmarks - patient MW

table 6.21

Processed data;

Patient #1 (RB)

Test No	X_P	Y_P	Z_P	X_Q	Y_Q	Z_Q	X_R	Y_R	Z_R
1	0.7	17.4	12.0	2.9	16.1	12.4	-0.4	24.2	13.1
2	1.7	21.3	14.1	-4.2	19.3	13.4	-7.1	26.1	11.5
3	0.1	20.7	12.8	-1.0	20.2	10.5	-8.8	27.0	12.9
4	2.9	21.8	12.0	-4.9	20.3	11.6	-11.5	22.1	3.8
5	2.5	22.1	11.6	-3.4	19.1	11.6	error	error	error
6	4.1	22.1	11.8	-5.4	20.1	10.8	-2.2	27.6	12.7
7	1.3	22.6	14.0	-5.1	21.3	11.3	-4.3	28.9	12.3
8	2.6	25.2	12.1	-6.5	23.4	9.5	-1.8	30.2	12.5
9	1.7	24.8	12.2	-1.3	22.8	10.7	-5.5	29.9	12.3

Data processed to provide the global coordinates of the wrist's flexion/extension axis on the radial and ulnar skin surfaces, and a point on the dorsal surface of the metacarpal joint for a finger – patient RB

table 6.22

Test No	PHI(x)	PHI(y)	PHI(z)	Wrist axis length	Mid-Wrist x	Mid-Wrist y	Mid-Wrist z	Length of Metacarpal
1	-14.1	-8.8	-31.8	2.6	1.8	16.75	12.2	7.8
2	-	-	-	6.3	-1.25	20.3	13.75	8.5
3	-	-	-	2.6	-0.45	20.45	11.65	10.7
4	-	-	-	8.0	-1	21.05	11.8	13.2
5	-	-	-	6.6	-0.45	20.6	11.6	-
6	-	-	-	9.8	-0.65	21.1	11.3	6.8
7	63.6	-22.5	11.7	7.1	-1.9	21.95	12.656	7.4
8	54.3	-15.8	11.5	9.6	-1.95	24.3	10.8	6.1
9	34.4	-27.4	34.2	3.9	0.2	23.8	11.45	8.4

The rotation of the wrist axis with respect to the 'global' coordinate axis system - patient RB
table 6.23

Test No	X_P	Y_P	Z_P	X_Q	Y_Q	Z_Q	X_R	Y_R	Z_R
1	-1.9	20.2	8.7	-9.9	19.1	6.8	0.9	27.7	8.6
2	5.5	23.9	10.7	-1.4	22.1	12.8	5.7	28.1	14.2
3	1.6	19.9	12.6	-5.7	18.5	12.3	0.8	26.3	13.1
4	-1.5	20.3	13.7	-6.2	18.7	12.3	0.3	26.7	12.7
5	-2.9	19.9	13.4	-4.1	19.9	12.4	error	error	error
6	4.4	18.2	11.6	-5.1	17.4	12.6	-1.5	25.4	13.2

Data processed to provide the global coordinates of the wrist's flexion/extension axis on the radial and ulnar skin surfaces, and a point on the dorsal surface of the metacarpal joint for a finger – patient MW
table 6.24

Test No	PHI(x)	PHI(y)	PHI(z)	Wrist axis length	Mid-Wrist x	Mid-Wrist y	Mid-Wrist z	Length of Metacarpal
1	59.7	-13.9	8.3	8.3	2.1	20.8	9.7	25.7
2	-50	16.6	14.1	14.2	8.9	24.8	9.7	19.9
3	14	-2.7	10.8	7.4	5.3	20.6	12.8	21.5
4	38.9	-15.6	19.1	5.2	0.9	21.1	14.4	25.9
5	89.7	-40.5	0.3	1.6	-2.3	19.9	13.9	error
6	-53.4	6.1	4.6	9.6	9.2	18.6	11.1	19.5

The rotation of wrist axis with respect to the 'global' coordinate axis system - patient MW
table 6.25

It can be seen that the results are disappointing. For patient RB, the calculated length of the wrist axis varied between 2.6 and 9.8 cms and the length of the metacarpal varied between 6.1 and 13.2 cms. For patient MW, the calculated length of the wrist axis varied between 1.6 and 14.2 cms and the calculated length of the metacarpal varied between 19.5 and 25.7 cms. It was decided that the two sources of error were (i) identification of anatomical landmarks, and (ii) the small size of the machine's enclosure and the associated errors in taking accurate measurements. Clearly, errors of this order were unacceptable and the method was not pursued.

CHAPTER 7
ANALYSIS AND RESULTS

7.1 Introduction

The patient data was obtained from the clinical trials in Berlin and the analysis of this data is described in section 7.2. The interpretation of the data concentrated on the changes in finger joint angles attributable to CPM, and on the changes in force data (maximum, minimum and mean values, standard deviations and percentage data above mean value) which would be caused by reductions in the work required by the CPM machine to move finger joints through fixed angles.

The single actuator machine was developed for use in Dundee. Rather than repeat the Berlin tests and repeat the same interpretation of force data, it was decided to use this machine to evaluate the suitability of the linkage for clinical use. This is discussed in chapter 8.

Methods to determine the lengths of the phalanges by direct measurement from the edges of the Berlin machine and from a space frame, rather than use the lengths predicted in section 6.1 (page 164), are discussed in section 7.3

Finally, studies to improve the linkage by reducing its size were successfully completed and these are described in section 7.4

7.2 Analysis of patient data results obtained using the twin actuator machine - Berlin data

The patients chosen for the Berlin study were not random samples from a single clinical group, so it would not have been appropriate to perform a collective statistical analysis upon the data obtained from these patients, because this data was not representative for a defined population. Instead, the patients were regarded as unique representatives from different statistical populations (their different diagnoses are listed in table 6.15, pages 188-190; Dupuytren's contractures, joint contusions etc). They had the common distinction of having being identified by clinical prescribers as having the potential for improvement in hand function if CPM treatment were applied. It was decided to interpret the data by investigating each patient individually, in such a way that the effects of CPM on representative patients from different clinical categories could be summarised. Each patient would be his/her own control, so comparing before-and-after results could assess the effects of CPM. The finger joint angle data was processed (in the manner described in section 6.3.3, page 197) to obtain the following;

(1) The effect of CPM treatment on **changes** in finger joint angles, pre- and post- each CPM treatment session, throughout the entire course of CPM treatment (shown in appendix 5.2, *Plots of the changes in patients' finger joint angles; pre- and post- CPM treatment)*. The interpretation is discussed in section 7.2.1

(2) The percentage occurrences of particular changes in finger joint angles, provided by **each** CPM treatment session (shown in appendix 5.3, *Details of the percentage occurrences of changes in patients' finger joint angles, provided by each CPM treatment session)*. The interpretation is discussed in section 7.2.2

(3) The effect of **all** CPM treatment sessions on finger joint angles (shown in appendix 5.4, *(Mean and standard deviation values for the maximum and minimum finger joint angles, recorded before and after each CPM treatment session, for the entire treatment period of each patient)*. The interpretation is discussed in section 7.2.3

7.2.1 Interpretation of the plots of the changes in patients' finger joint angles; pre- and post- each CPM treatment session *(appendix 5.2)*

The method used for interpreting the data is described below, using the example of patient #15 (ML), who had a torn fibrocartilage in the PIP joint in her left little finger. The patient was seen on twenty-two occasions and her ranges of active finger joint motion were measured both before and after CPM treatment using the European neutral-flexion-extension method. The data is listed in appendix 5.1 and reproduced in table 7.1 below.

visit 1		*visit 2*		*visit 3*		*visit 4*		*visit 5*	
before	after	before	after	before	after	before	after	before	after
0 30 80	0 20 80	0 30 80	0 20 85	0 30 80	0 15 90	0 30 80	0 20 80	0 20 90	0 20 95

visit 6		*visit 7*		*visit 8*		*visit 9*		*visit 10*	
before	after	before	after	before	after	before	after	before	after
0 40 80	0 30 85	0 45 90	0 25 90	0 30 90	0 30 90	0 30 80	0 30 90	0 30 90	0 30 95

continued/

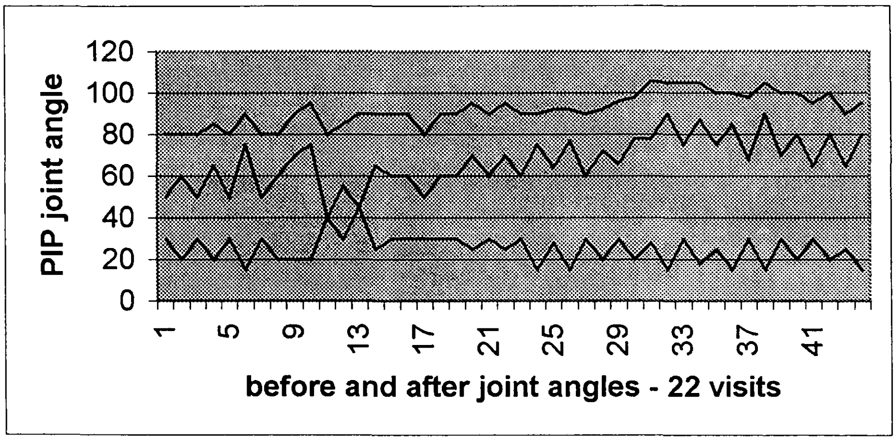
visit 11		*visit 12*		*visit 13*		*visit 14*		*visit 15*	
before	after	before	after	before	after	before	after	before	after
0 30 90	0 25 95	0 30 90	0 15 90	0 28 92	0 15 92	0 30 90	0 20 92	0 30 96	0 20 98

visit 16		*visit 17*		*visit 18*		*visit 19*		*visit 20*	
before	after	before	after	before	after	before	after	before	after
0 28 106	0 15 105	0 30 105	0 18 105	0 25 100	0 15 100	0 30 98	0 15 105	0 30 100	0 20 100

visit 21		*visit 22*	
before	after	before	after
0 30 95	0 20 100	0 25 90	0 15 95

Ranges of active finger joint motion before & after CPM treatment, measured using the European neutral-flexion-extension method.
table 7.1

The zigzag changes in her maximum flexion and extension joint angles, together with the changes in joint range of motion, are illustrated below in figure 7.1



'Before and after' zigzag changes in maximum flexion & extension joint angles, and joint range of motion - patient #15
figure 7.1

It is clear that the zigzag changes are cyclic improvement & regression, associated with the application & removal of CPM therapy. There is an overall improvement trend in both maximum flexion angle (upper plot) and joint range of motion (middle plot) but virtually no change in maximum extension angle (lower plot).

This process was used for all the patients and the plots of the before-and-after maximum extension, maximum flexion and ROM results, are shown in appendix 5.2

The patient's (#15) gains in maximum flexion & extension angles, and the overall gain in ranges of joint motion achieved during each CPM treatment session (ignoring the regression which occurred between sessions), are listed below in table 7.2, together with mean and standard deviation values.

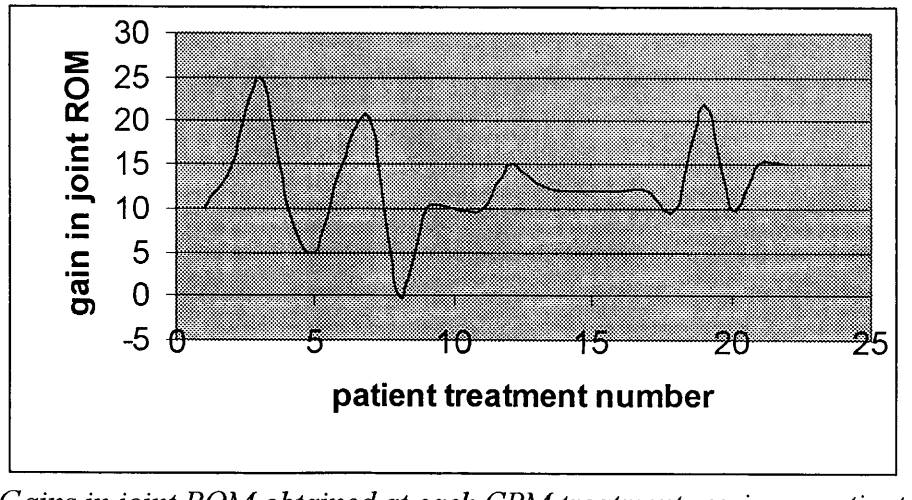
PIP5: variation in improvements provided by treatment

visit no:	1	2	3	4	5	6	7	8	9	10	11	12	13
gain in maximum joint extension angle	10	10	15	10	0	10	20	0	0	0	5	15	13
gain in maximum joint flexion angle	0	5	10	0	5	5	0	0	10	5	5	0	0
Gain in ROM	10	15	25	10	5	15	20	0	10	10	10	15	13

visit no:	14	15	16	17	18	19	20	21	22	mean	std. dev.
gain in maximum joint extension angle	10	10	13	12	10	15	10	10	10	9.45	5.29
gain in maximum joint flexion angle	2	2	-1	0	0	7	0	5	5	2.95	3.31
gain in ROM	12	12	12	12	10	22	10	15	15	12.64	5.18

Gains in maximum flexion & extension angles, and overall gain in ranges of joint motion, achieved during each CPM treatment session - patient #15
table 7.2

It is apparently strange that the standard deviation value for the maximum flexion angle is larger than the mean value. This is explained by the fact that on nine occasions, no gains were achieved but these 'zero' values also contribute towards the calculation of the standard deviation value. Gains in joint ROM were obtained at *each* CPM treatment session, with a mean gain of 9.5 degrees and a standard deviation of 5.3 degrees (see above) for all the treatment sessions. This is illustrated in figure 7.2 below;



Gains in joint ROM obtained at each CPM treatment session – patient #15
figure 7.2

Again, this approach to interpret the data was followed for all the patients and the plots of their results are provided in appendix 5.2.

The data in table 7.2 is summarised in the following manner;

			gain in joint extension angle		gain in joint flexion angle		gain in joint range of movement	
	PATIENT		**mean**	**std dev**	**mean**	**std dev**	**mean**	**std dev**
15	ML *n = 22*	PIP5	9.5	5.29	3.0	3.31	12.6	5.18

These are the *overall changes* in joint angles, obtained during the *complete course* of CPM treatment. This result was compiled with the results for all the patients, and they are shown below in table 7.3.

			gain in joint extension angle		gain in joint flexion angle		gain in joint range of movement	
	PATIENT		**mean**	**std dev**	**mean**	**std dev**	**mean**	**std dev**
1	RB *n = 39*	MCP2	-0.13	3.67	4.10	5.97	3.97	7.53
		MCP3	0.64	3.03	4.87	6.25	5.51	6.68
		MCP4	0.64	3.24	4.23	6.56	4.87	7.80
		MCP5	-0.38	4.29	6.79	7.80	6.41	8.84
		PIP2	-1.15	2.65	-0.64	5.57	-1.79	6.15
		PIP3	-1.03	2.58	-1.67	5.59	-2.69	6.49
		PIP4	-1.03	3.03	0.90	7.83	-0.13	9.30
		PIP5	-0.13	4.16	0.90	7.24	0.90	7.50
		DIP2	1.41	4.93	0.38	7.28	1.79	7.97
		DIP3	0.90	5.05	0.64	4.41	1.28	6.77
		DIP4	0.26	2.76	1.67	4.43	2.18	5.41
		DIP5	0.13	4.46	1.03	7.18	1.03	8.64
		MCP2+MCP3+ MCP4+MCP5	0.77	7.30	20.00	19.68	20.77	21.91
		PIP2+PIP3+ PIP4+PIP5	-3.33	7.87	-0.51	18.97	-3.72	22.38
		DIP2+DIP3+ DIP4+DIP5	2.69	10.12	3.72	15.01	6.28	16.94
		MCP2+PIP2+ DIP2	0.13	6.35	3.85	11.85	3.97	13.78
		MCP3+PIP3+ DIP3	0.51	7.66	3.85	10.53	-0.38	16.38
		MCP4+PIP4+ DIP4	-0.13	4.31	6.79	11.63	6.92	13.04
		MCP5+PIP5+ DIP5	-0.38	8.04	8.72	12.75	8.33	15.16
3	MK *n = 10*	PIP4	0.5	1.50	2.0	4.58	2.50	5.12

continued /

	PATIENT		gain in joint extension angle		gain in joint flexion angle		gain in joint range of movement	
			mean	std dev	mean	std dev	mean	std dev
4	GZ *n = 11*	PIP2	3.6	6.06	0.9	4.17	4.6	8.38
		PIP3	1.8	6.83	-2.7	7.19	-0.9	9.73
		PIP4	0	4.77	-2.7	4.94	-2.3	7.79
		PIP5	2.3	6.17	-0.9	5.96	0.5	9.40
5	CDB *n = 20*	PIP4	-0.6	2.71	4.25	5.54	3.65	5.84
6	AM *n = 25*	PIP3	4.0	5.10	0.4	4.10	4.6	6.18
		PIP4	2.4	3.20	0.4	1.96	3.2	3.71
7	CM *n = 15*	PIP2	3.67	8.65	-1.33	6.18	2.67	9.81
		PIP3	9.0	12.0	-0.33	4.27	9.0	11.58
		PIP4	4	6.39	-1.0	5.84	1.33	11.69
		PIP5	7.0	7.56	-3.33	6.8	2.67	10.62
13	Ma *n = 31*	PIP2	0	0	9.6	3.93	9.6	3.93
		PIP4	0	0	3.65	4.39	3.65	4.39
		PIP5	0	0	6.68	4.16	6.68	4.16
14	Ha *n = 39*	MCP2	0.89	2.69	5.23	3.64	6.2	4.27
		MCP3	0.54	2.44	4.57	3.34	5.1	4.60
		PIP2	1.79	3.49	7.36	5.56	9.15	5.80
		PIP3	1.4	3.91	6.8	5.54	8.2	7.02
15	ML *n = 22*	PIP5	9.5	5.29	3.0	3.31	12.6	5.18
16	Ka *n = 39*	MCP4	1.29	6.30	4.23	7.17	5.52	8.11
		MCP5	-2.26	8.61	11.77	7.82	9.52	7.47
		PIP4	-.07	6.28	3.55	7.43	4.52	8.46
		PIP5	1.13	6.06	4.19	8.08	5.32	8.66
17	Jo *n = 4*	PIP4	2.5	5.59	2.5	2.50	5	6.12
18	Wi *n = 28*	MCP2	2.14	3.11	-1.96	5.23	0.18	5.59
		MCP3	-1.07	3.37	-1.25	3.44	-2.32	4.91
		MCP4	0.36	2.97	-1.79	4.86	-1.43	4.79
		PIP2	0.54	2.44	-1.25	5.92	-0.71	5.78
		PIP3	0.18	3.40	-0.54	4.69	-0.54	4.88
		PIP4	0.0	3.54	-1.79	5.04	-1.79	5.38
		DIP2	-0.36	1.86	-1.43	4.97	-1.96	4.88
		DIP3	-0.18	2.11	-1.96	5.72	-2.32	5.59
		DIP4	1.07	2.45	-0.71	5.30	0.18	4.33

Summary of the variation in joint angle improvement for all patients, obtained by all CPM treatment sessions - averaged
table 7.3

These results are discussed for each patient.

PATIENT #1 - RB (all joints, right hand)

Positive results; PIP2 flexion angle increased from 55 to 75 degrees; PIP2 ROM increased from 55 to 70 degrees. *Negative results;* The sum of extension angles for all the joints in the index finger was noticeably erratic. There was no overall discernible gain in ROM for this patient.

PATIENT #3 - MK (digit 4 PIP, right hand)

Positive results; The patient could gain an increase in maximum flexion angle of up to 10 degrees at each treatment session. There was an overall gain in ROM of 10 degrees. *Negative results;* The beneficial effects were minimal.

PATIENT #4 - GZ (digit 3 PIP, right hand)

Positive results; Increases in ROM of up to 20 degrees were obtained after CPM treatment. *Negative results;* The beneficial gains were difficult to identify for individual joints. However, a net improvement in ROM from 70 to 120 degrees was obtained for the sum of all the PIP joints.

PATIENT #5 - CDB (digit 4 PIP, right hand)

Positive results; Overall gain in ROM from 10 to 25 degrees. *Negative results;* Decrease in PIP4 maximum extension angle from 30 to 20 degrees but this was offset by a gain in flexion angle from 30 to 45 degrees.

PATIENT #6 - AM (digits 3, 4 and 5 PIPs, right hand)

Positive results; Gain in ROM from 20 to 30 degrees for PIP4. *Negative results;* Beneficial effects were marginal.

PATIENT #13 - Ma (digits 2 and 5 PIPs, left hand)

Positive results; Maximum flexion angle for PIP2 increased from 40 to 60 degrees. *Negative results;* Virtually no change in the sum of the ROM for all the PIP joints.

PATIENT #14 - OH (digits 2 and 3 PIP, left hand)

Positive results; ROM increased from 30 to 60 degrees for PIP2 and from 35 to 70 degrees for PIP3. *Negative results;* None.

PATIENT #15 - ML (digit 5 PIP, left hand)

Positive results; ROM increased from 50 to 80 degrees for PIP5. *Negative results;* None.

PATIENT #16 - UK

Positive results; ROM increased from 60 to 80 degrees for PIP4, with a steady trend. *Negative results;* Maximum extension angle decreased from 20 to 10 degrees. There was marginal change in PIP5.

PATIENT #17 - Jo

Positive results; Overall gain in ROM for PIP4 from 30 to 45 degrees. *Negative results;* None.

PATIENT #18 - Wi

Positive results; The gain in the sum of the flexion angles (MCP+PIP+DIP) was from 210 to 220 degrees for the index finger; from 230 to 240 degrees for the middle finger; and from 170 to 210 degrees for the ring finger. The gain in sum of the ROM angles was from 210 to 240 degrees for the MCP joint angles; from 240 to 275 degrees for the PIP joint angles; and from 150 to 170 degrees for the DIP joint angles. *Negative results;* These changes are minimal but nevertheless observable.

Errors in measuring finger joint angles

The joint angles were measured with a finger protractor and recorded in 5-degree increments, so the maximum error for each measurement might be 2.5 degrees. Assuming this is the worst possible case, then the error in the measurement for joint range of motion might be 5^0 (i.e. 2.5^0 for flexion + 2.5^0 for extension). The maximum errors associated with the measurement of the patients' nominal ranges of motion are shown below. The largest error was associated with patient #5, who had limited ROM in the PIP joint. The joints of particular interest to the therapists are highlighted.

patient	*joint*	*ROM*	*error*	*patient*	*joint*	*ROM*	*error*
#1	MCP2	60	8.3	#6	PIP3	35	14.3
	PIP2	65	7.7		PIP4	35	14.3
	DIP2	25	25	#13	PIP2	50	10
	MCP3	70	7.1		PIP4	25	20
	PIP3	75	6.7		PIP5	35	14.3
	DIP3	10	50	#14	PIP2	55	9.1
	MCP4	60	8.3		PIP3	70	7.1
	DIP4	15	33	#15	PIP5	70	7.1
	MCP5	65	7.7	#16	MCP4	75	6.7
	PIP5	55	9.1		PIP4	75	6.7
	DIP5	20	25		MCP5	70	7.1
#3	DIP4	30	16.7		PIP5	65	7.7
#4	PIP2	35	14.3	#17	PIP4	35	14.3
	PIP3	30	16.7	#18	DIP2	55	9.1
	PIP4	20	25		DIP3	70	7.1
	PIP5	20	25		DIP4	45	11.1
#5	PIP4	20	25				

Maximum errors in the measurement of patients' nominal ranges of motion
table 7.4

Discussion – changes in finger joint angles

Overall improvements obtained during the complete course of treatment (listed in table 7.3), and also improvements obtained at each CPM treatment session (see plots in appendix 5.2), were achieved but they were not consistent. With the benefit of hindsight, it could be stated that CPM treatment was inappropriate for some patients. For instance, the treatment of patients with Sudeck contractures (patients #1 and #4) and the patient who had attempted suicide (patient #7) were probably complicated by psychological factors. Furthermore, a number of these patients were receiving physiotherapy, which could be expected to influence the results. Notwithstanding these comments, the principal findings were that CPM treatment almost invariably resulted in some improvement in joint ROM at each treatment session.

7.2.2 Interpretation of the details of the percentage occurrences of changes in patients' finger joint angles, provided by each CPM treatment session *(appendix 5.3)*

Whereas section 7.2.1 (above) summarised the *overall averaged changes* in joint movement which occurred during the complete period of CPM treatment, the percentage occurrences of changes in patients' finger joint angles, provided by *each individual* CPM treatment session, is summarised in appendix 5.3. To take an example, on 16 out of 39 occasions (i.e. 41%) when patient #1 (RB) attended for treatment, she obtained a 5 degree increase in MCP2 joint maximum flexion angle after treatment. It can be seen that the results shown in this appendix are generally very encouraging. Although some reductions in joint angles did occur (especially for the Sudeck patient RB) which are difficult to explain, the overall trend was encouraging with gains of 10 - 20 degrees being quite common.

7.2.3 Mean and standard deviation values for the range of movement for finger joint angles, recorded before and after each CPM treatment session, for the entire treatment period of each patient *(appendix 5.4)*

A study was made of the changes in joint maximum extension, flexion and ROM angles, together with standard deviation values about the mean values, both before and after each CPM session. The results for the mean changes in ranges of motion are shown below.

PATIENT	**Mean gains in joint ROM with subsequent reductions in s.d. about mean values**	**Mean gains in joint ROM with subsequent increases in s.d. about mean values**
MK	PIP4 (25.5 *to* 28.0; 5.22 *to* 2.45)	
GZ	PIP2 (34.1 *to* 38.6; 9.0 *to* 6.77)	
	PIP5 (19.1 *to* 19.6; 9.49 *to* 8.91)	
CDB	PIP4 (9.75 *to* 13.4; 6.42 *to* 5.40)	
AM	PIP3 (32.8 *to* 37.4; 4.92 *to* 4.72)	
	PIP4 (22.2 *to* 25.4; 3.49 *to* 4.22)	
CM	PIP3 (35.33 *to* 44.33; 12.91 *to* 11.86	PIP2 (40.67 *to* 43.33; 13.52 *to* 13.74)
	PIP5 (29.67 *to* 32.33; 15.87 *to* 14.16)	PIP4 (25.67 *to* 27.0; 19.69 *to* 20.07)
Ma	PIP4 (26.61 *to* 30.26; 4.09 *to* 3.82)	PIP2 (44.35 *to* 53.97; 4.71 *to* 5.08)
	PIP5 (31.94 *to* 38.61; 3.03 *to* 2.95)	

continued /

/ continued

PATIENT	Mean gains in joint ROM with subsequent <u>reductions</u> in s.d. about mean values	Mean gains in joint ROM with subsequent <u>increases</u> in s.d. about mean values
Ha	PIP2 (49.41 *to* 58.56; 9.20 *to* 7.83) PIP3 (60.92 *to* 69.13; 10.88 *to* 8.93)	
ML		PIP5 (63.2 *to* 76.8; 10.49 *to* 10.78)
Ka	MCP4 (71.4 *to* 76.9; 6.70 *to* 6.31) PIP4 (72.1 *to* 76.6; 9.23 *to* 7.23) PIP5 (64.5 *to* 69.8; 7.97 *to* 6.15)	MCP5 (66.3 *to* 75.8; 6.09 *to* 6.97)
Jo		PIP4 (31.25 *to* 36.25; 2.17 *to* 7.40)
Wi	DIP4 (46.25 *to* 46.79; 4.15 *to* 3.83)	

Mean gains in ROM, with subsequent reductions and increases in s.d. about mean values
table 7.5

PATIENT	Mean decreases in joint ROM with subsequent <u>reductions</u> in s.d. about mean values	Mean decreases in joint ROM with subsequent <u>increases</u> in s.d. about mean values
GZ	PIP3 (31.8 *to* 30.9; 10.93 *to* 9.25) PIP4 (22.3 *to* 20.0; 8.08 *to* 7.69)	
Wi		MCP4 (73.21 *to* 71.79; 7.93 *to* 8.15) DIP3 (66.07 *to* 63.75; 3.86 *to* 5.11)

Mean decreases in ROM, with subsequent reductions and increases in s.d. about mean values
table 7.6

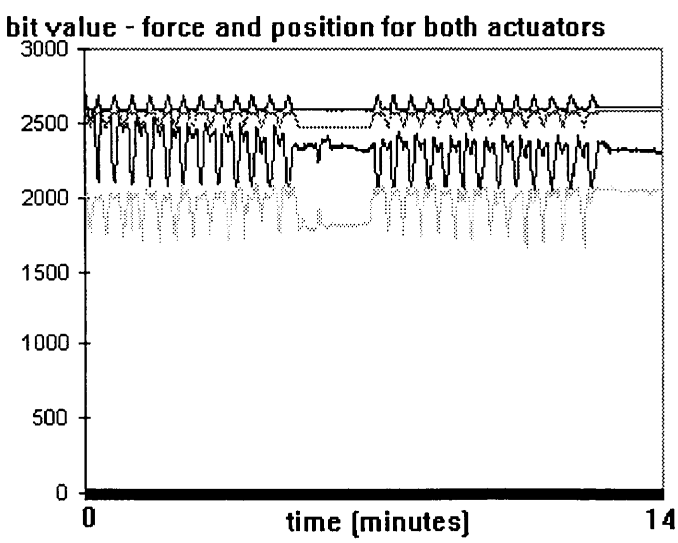
Not surprisingly, individual CPM treatment sessions on the majority of the joints with severe movement restrictions (i.e. sixteen out of twenty two) resulted in both gains in joint ROM and reductions in s.d. about mean values (table 7.5). The reason might be that the patients gained an increase in ROM caused by stretching of tissue, which gradually decreases after the removal of CPM. A more 'normal' distribution of joint ROM might be expected after a period of rest for the tissue, though the reason is not definitely known. For those sessions when gains in ROM were associated with increases in s.d., the *minimal* increases in s.d. were considered to be so small as to be regarded as insignificant. Similarly, the decreases in ROM for the two patients GZ and Wi were so small as to be considered insignificant.

7.2.4 Interpretation of data relating to actuator force and position data

It has been repeatedly stressed by Salter *et al* that CPM treatment requires slow, gentle and pain free joint movement and that the application of force should not be a 'brutal' method of stretching tissue. This begs the question, why should CPM forces be measured at all, if their magnitudes are low and the benefit of CPM lies in *movement* not *application of force*? The answer lies in the recognition that CPM treatment always requires the application of some force and if this force has the effect of providing an increase in joint range of motion, it might be supposed that there would be a correlation between the changes in force patterns and changes in joint angle. Furthermore, there are those who advocate gentle passive stretching of tissue to increase joint ROM, so force measurement in both CPM and passive stretching modes might provide data for a comparison.

In this section, data are presented as the variations in force and position, for one or both actuators, against the time for which data were captured. The force and position data is expressed in bit value since it is the form of the data, not the absolute magnitudes, which is considered. The sampling frequency for data capture was 2.0124 samples/second.

The effects of CPM treatment have to be considered as long term so, in the first instance, the observable trends in force signals have to be considered on a macroscopic level. It would have been rewarding to have consistently observed trends like the one shown in figure 7.3 below, where there is an obvious trend in the reduction of the force signal;

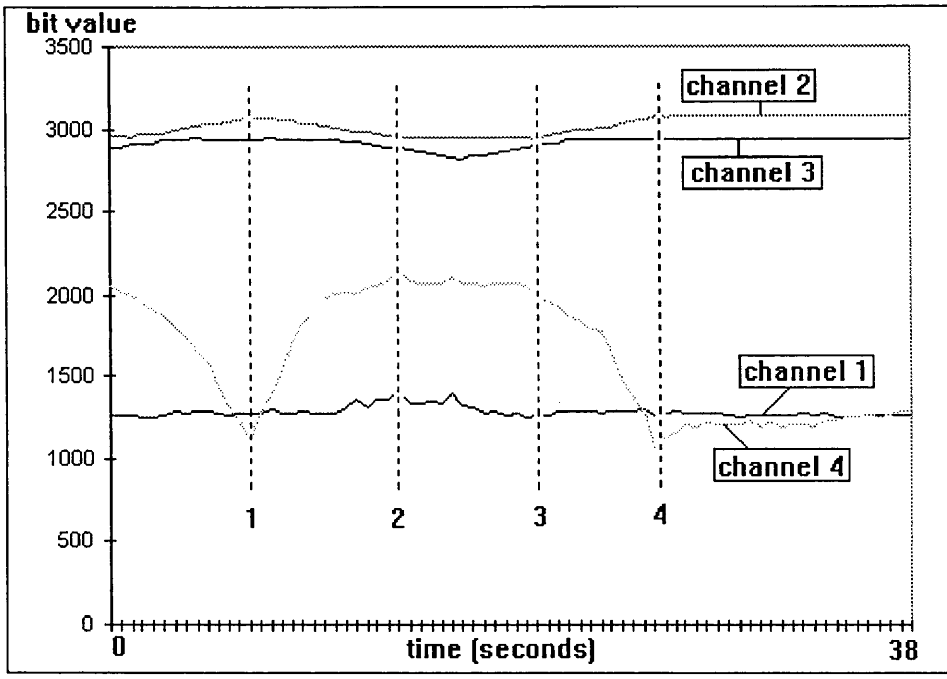


There is an obvious trend in force reduction (signal second bottom), particularly in the first period of cyclic movement.

source:
patient 9: GE48
data values: 1-1700

Example of the trend in the reduction of the signal for actuator force
figure 7.3

The form of the data should also be considered for a single cycle of movement, in order to determine the factors that might influence it. An example of patient data that illustrates a single cycle of movement for the two actuators is illustrated below in figure 7.4. It can be seen that actuator 2's potentiometer signal (channel 2) and force signal (channel 4) are clearly coupled together. This actuator moves from position 1 (highest potentiometer signal bit value) to position 2, where it pauses whilst actuator 1 (potentiometer signal channel 3) moves. The reversal of movement in actuator 1 (channel 3) causes a small change in its associated force signal (channel 1) but the change is small because the actuator movement is also small. The force signal for actuator 2 (channel 4) remains relatively stable until the actuator begins to move again (position 3). The force signal then decreases to its original level (position 4).



source:
patient 3: MK10
data values:
1765 - 1840

Example of patient data that illustrates a single cycle of movement for the two actuators
figure 7.4

7.2.4.1 Factors which influence the signal patterns for actuator force and position data

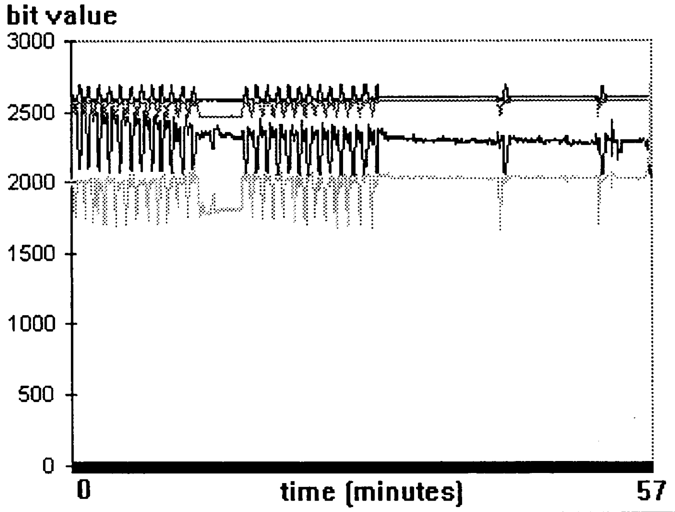
The forms of the data illustrated in the two figures above (7.3 and 7.4) are not unsurprising, but inspection of other data revealed the following factors which effect data;

- passive tissue stretching
- repositioning the machine or finger thimble
- active movement by the patient
- 'force' coupling between fingers

These are discussed below.

The effect of passive tissue stretching

Figure 7.3 showed a trend in the reduction of a force signal during the cyclic movement of CPM. However, figure 7.5 below shows an example of how this trend continues during passive tissue stretching. In the latter case, the actuator rod was stopped at its furthest position to motion and the force signal recorded continuously. It is not clear whether the trend in the reduction in the force signal occurs because of CPM movement or passive stretching. However, passive stretching is uncomfortable for a patient, because the continuous pressure restricts blood flow. Cyclic movement is more tolerable.



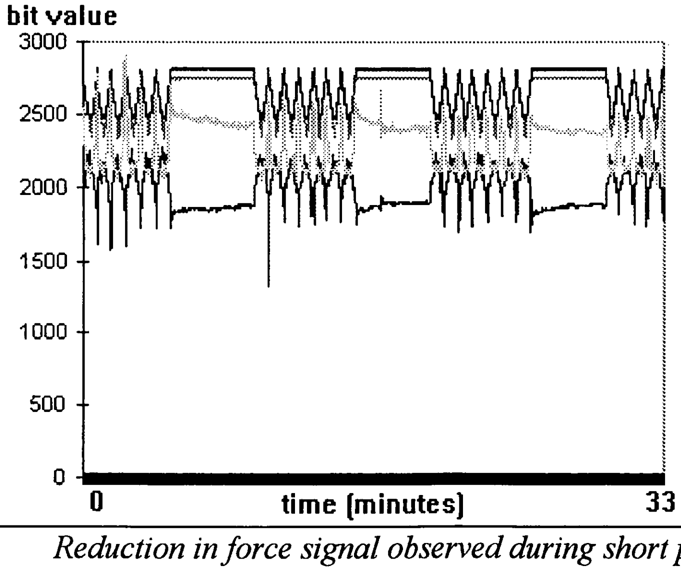
The relaxation in force signal, apparent in the CPM phase (trace second from the bottom) continues in the prolonged passive stretching phase.

(NB Active finger movement is also observable).

source:
patient 9: GE48

Reduction in force signal observed during prolonged period of passive tissue stretching
figure 7.5

The trend is not restricted to *prolonged* passive stretching because trends in force signals also occur in the short rest periods (figure 7.6 below), though the same comment about patient discomfort applies;



Notice trends in both force channels during the pause periods. The lower signal registers a high bit value for a low force.

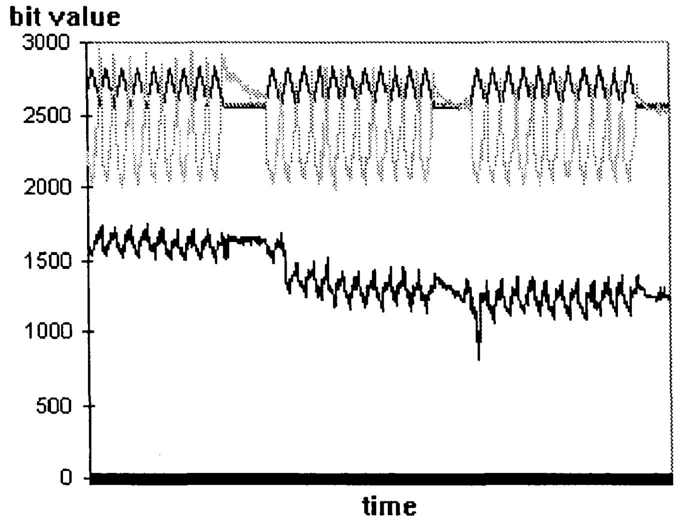
(The lower trace is inverted in the sense that it represents a high magnitude of force for a low bit value and a low force for a high bit value. Also notice the active motion).

source:
patient 13: Ma50
data values: first 4000 points

Reduction in force signal observed during short period of passive tissue stretching
figure 7.6

The effect of repositioning the machine or finger thimble

The 'weak link' in the application of the CPM machine is the elastic surgical tape which was used to apply the actuator thimble to a finger. This tape could slip and detach itself from the skin or it could stretch. Similarly, whenever the patient felt discomfort because of blood flow restriction, pinching of the skin etc, he or she would inevitably readjust the position of the actuator thimble on the finger. In either case, the position of the load cell with respect to the finger joints would alter with an inevitable change in force signal. This is illustrated in figure 7.7 below.



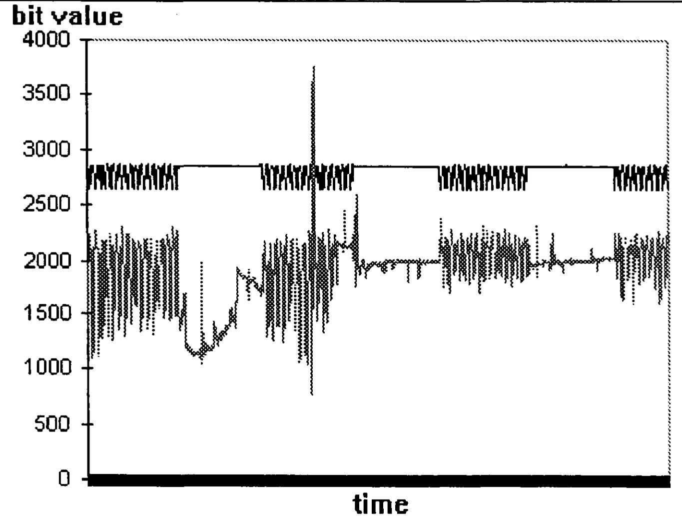
Dramatic change in force signal (for lower force channel) without an obvious cause but probably attributable to repositioning of machine or thimble

source:
patient 7: CM9
data values: 1-2400

Effect of machine or finger thimble repositioning upon CPM force signal
figure 7.7

The effect of active movement by the patient

The observation that patients have active movement during CPM is shown in figures 7.8 & 7.9

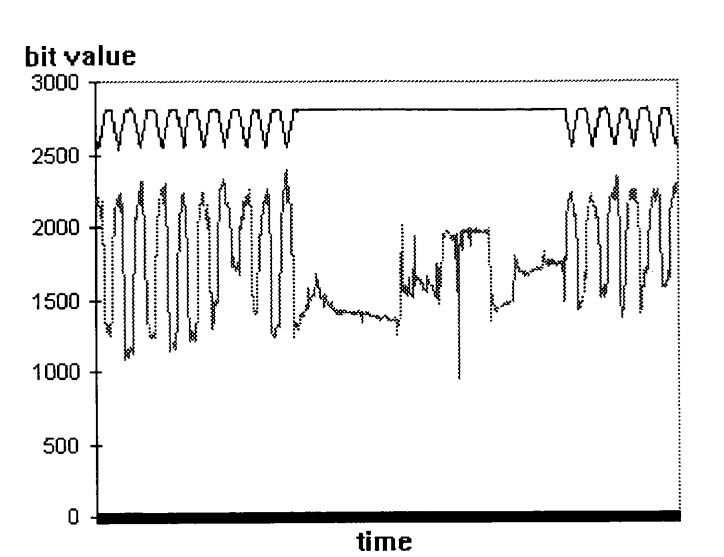


Active movement is evident in the second period of CPM movement. This movement has resulted in repositioning of the machine or the finger thimble, so the range of force values for the third period of movement is entirely different to the first.

source:
patient 5: CDB14
data values: channels 2 and 4
first 4000 data values

Effect of active movement by the patient, during cyclic movement, upon CPM force signal
figure 7.8

More usually, the position of the machine or the thimble is readjusted in the pause period;

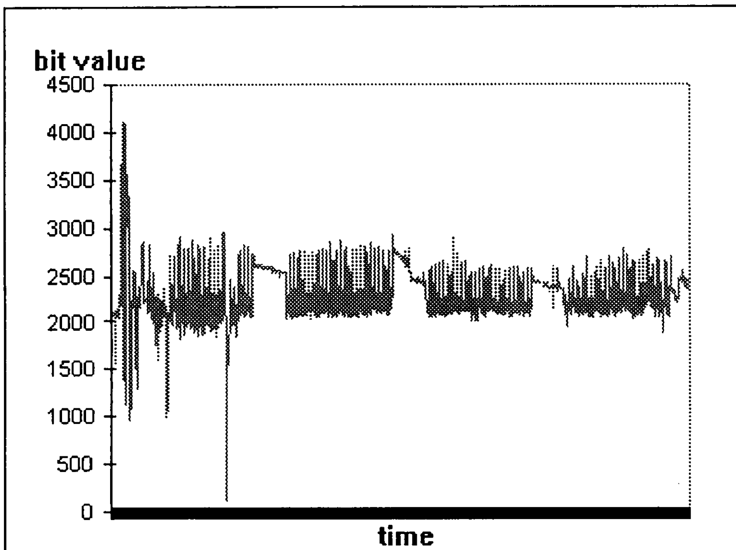


Active movement in the pause period. Some patients did not like the lack of movement because blood flow is stopped. The patient involuntarily moves his finger to relieve the feeling of numbness and cold. The range of min/max values on either side of the active movement has altered.

source:
patient 5: CDB23
channels 2 and 4,
data values 1400-2660

Effect of active movement by the patient, during paused movement, upon CPM force signal
figure 7.9

It was noticeable that active movement was very common in first period of cyclic movement, when the machine and patient 'settled in';



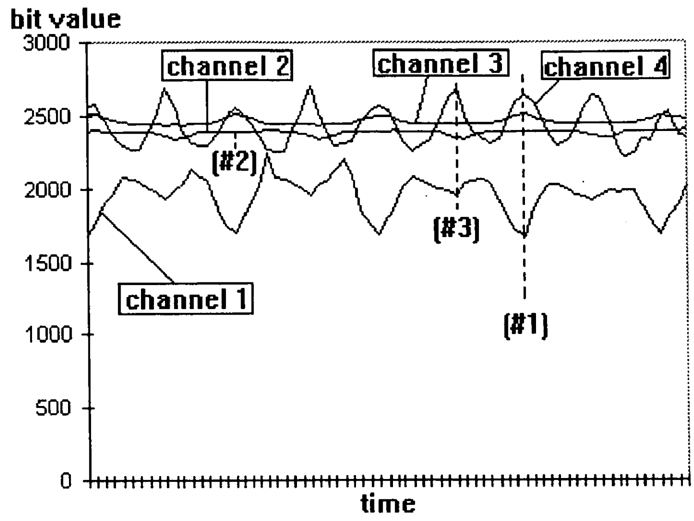
The first period of movement especially, and the second less so, show settling in.

source:
patient 6: AM16
data values:
channels 2 and 4,
data values 1-3500

Effect of active movement in first period of cyclic movement, upon CPM force signal
figure 7.10

The effect of coupling between fingers

There was consistent evidence that force data obtained from an actuator applied to a finger was affected by a contraction in its adjacent finger. This was the predominant factor that influenced the form of a force signal in an unpredictable manner. An example is shown in figure 7.11 on the next page;

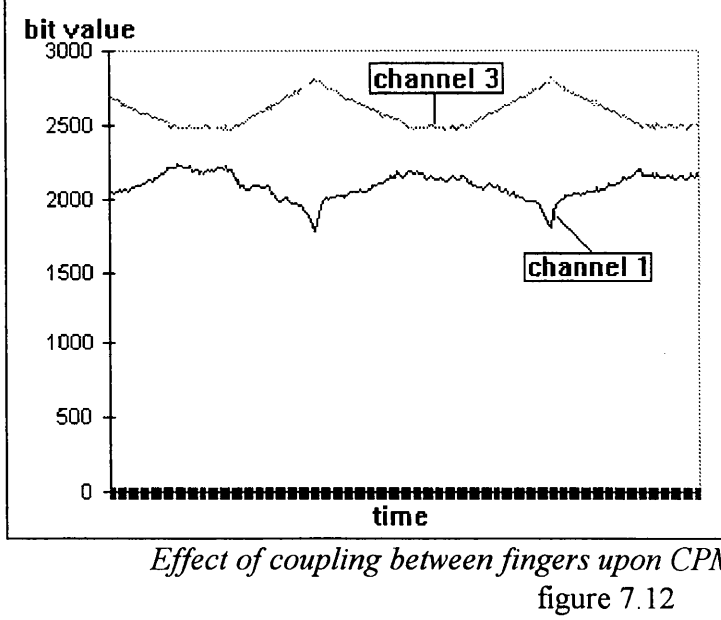


source:
patient 6: AM29
data values: 1720-1790

The force signal for actuator 1 (channel 1) reaches its lowest bit values at the same time as its associated potentiometer signal (channel 3) reaches its peak bit value (#1). The potentiometer for actuator 2 (channel 2) is immobile (#2) when it waits for actuator 1's potentiometer (channel 3) to move. When actuator 1's potentiometer (channel 3) retains a static value, it could be expected the same actuator's force signal (channel 1) would also remain static. In fact, channel 1 shows an irregularity (#3) which coincides with actuator 2's peak values for its force signal (channel 4). This illustrates that the forces are coupled together for the two fingers.

Effect of coupling between fingers upon CPM force signal – example 1
figure 7.11

The effect is also shown for another patient in figures 7.12, 7.13, and 7.14 below;

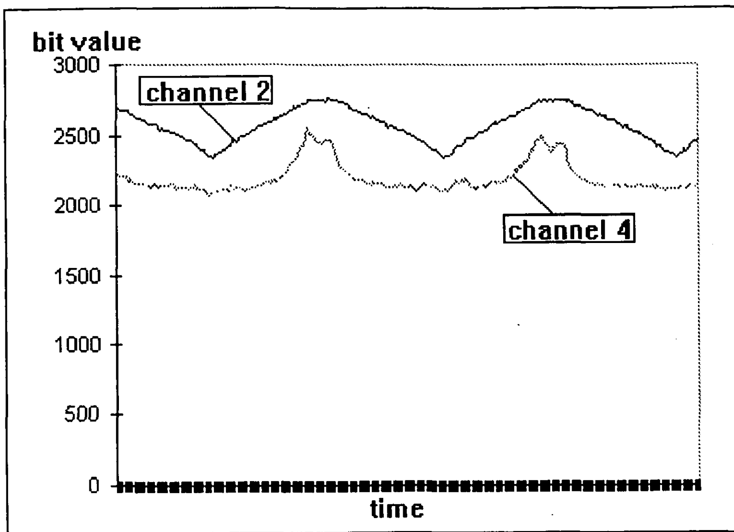


The force signal for actuator 1 (channel 1) has its minimum value when its associated potentiometer signal (channel 3) reaches its maximum value. These traces are not unexpected.

source:
patient 13: ma50
data values 2700-2950

N.B. Channels 1 and 3 are actuator #1

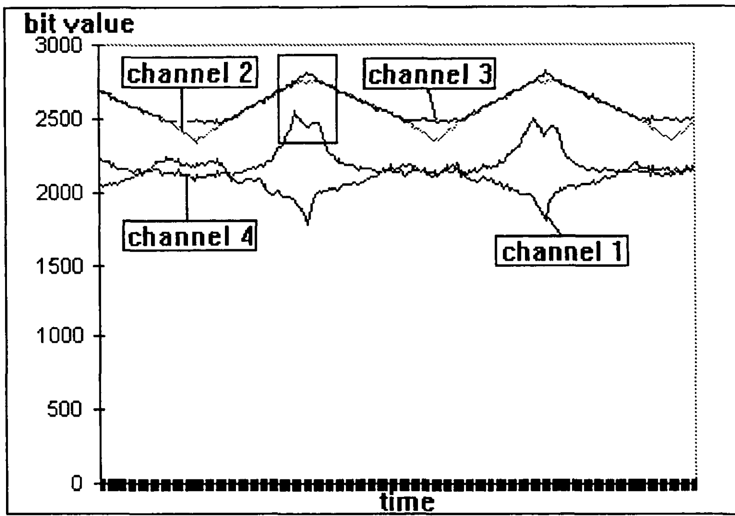
Effect of coupling between fingers upon CPM force signal – example 2
figure 7.12



The signals for actuator 2 (force channel 4 and potentiometer channel 2) are shown for the same period of movement. The unusual form of the force signal can only be explained when all four signals are viewed together (see below).

source:
patient 13: ma50
data values 2700-2950

Effect of coupling between fingers upon CPM force signal – example 3
figures 7.13



The potentiometer channels are very nearly superimposed (channels 2 and 3). It can be seen that the double hump in actuator 2's force signal (channel 4) coincides with the pause in actuator 1's potentiometer (channel 2). This is shown in the boxed section.

source:
patient 13: ma50
data values 2700-2950

Effect of coupling between fingers upon CPM force signal – example 4
figures 7.14

In conclusion, the form of the force data is affected by a number of factors that complicate its interpretation. Clearly, a conclusion drawn from an analysis of the corrective moments, exerted by the CPM machine about a contracted finger joint, would be flawed if these factors could not quantified. It is more appropriate to make a macroscopic interpretation of the force data and this was undertaken in the following form;

- An analysis of the maximum, minimum and mean data values for each period of cyclic movement (between the short pauses for passive stretching). This provides a means of observing gross trends.

continued/

- An analysis of the standard deviation and the percentage shift in data above the mean value, during each cycle of movement. This would provide a means of identifying any relaxation in contracted tissue because the energy applied by the machine (in the form of 'work done') would be expected to cause a shift in the percentage of force data about the mean.

The interpretation of the data was a highly time-consuming task because of the size of data obtained so unfortunately it was decided it would be impractical to develop force-displacement graphs also.

7.2.4.2 Interpretation of analysis results from the actuator position and force signal data

The interpretation of force data for 71 hours of CPM treatment was undertaken for patients MK (#3), GZ (#4), CDB (#5), AM (#6), CM (#7), IS (#8), GE (#9), RV (#10), EP (#12), Ma (#13) and Ha (#14). The recorded data were converted into force magnitudes (see section 6.3.2.3 - calibration of force and position transducers, page 193) and the results for each patient are shown in appendix 5.5 and plotted in figure 7.15 (summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients).

Tensile forces (i.e. pulling fingers into flexion) are shown as positive values and compressive forces (pushing into extension) are negative. The data caused by active movement were masked before the graphs were made, so that data interpretation is for cyclic CPM forces only.

The magnitudes of the CPM forces were surprisingly high. Patients repeatedly asked therapists to increase CPM force because they liked the feeling of tissue stretching. Peak tensile forces (for finger flexion) were 15 Newtons (patients #4 and #14), 14 Newtons (patient #3), 11 Newtons (patient #12) and 10 Newtons (patients #7 and #8). Peak compressive forces were 10 Newtons (patients #3, #9 and #14) and 9 Newtons (patient #5).

However, typical maximum forces were of the order of 7 Newtons tensile and 6 Newtons compressive. The problems of attaching the actuators to the fingers were often the limiting factors.

The data were found to be erratic and had to be inspected to determine the likely causes for its spikiness. Many examples of the causes were found. For instance, the problems of *repositioning the machine* were obvious for patient #3 for both actuators (see the second treatment session), patient #4 (actuator 1, second treatment) and patient #13 (actuator 1, second treatment). Data were affected by *active movement* seen for patient #5 (second and fourth treatments) and patient #13 (actuator 1, fifth treatment). Data were often affected at the beginning of treatment when *settling in* would occur, for instance patient #6 (actuator 1, twelfth treatment). Examples of these influencing factors were numerous and it is impractical to list them all. The trends in *maximum, minimum and mean force values* are obvious for patients #3 (actuator 1), #7 (actuator 2), #8 (actuator 2), #9 (actuator 1) and #10 (actuator 2) but not obvious in others. In an attempt to investigate further, an inspection was made of the *standard deviation values* of the data about their mean. These often fell quite dramatically at the beginning of a treatment session because of 'bedding in' and examples were patients #3 (actuator 1), #6 (actuator 2), #7 (both actuators), #8 (both actuators), #9 (both actuators), #10 (both actuators), #13 (both actuators) and #14 (both actuators). The s.d. sometimes increased at the end of a session, presumably because patients would have been told by the therapists that treatment was about to finish and they would begin to 'fidget' (patient #5, actuator 2).

Because of the spikiness of the results, a further study was made of the shift in the percentage of force data about their mean position (recognising that the latter does not alter much), on the grounds that work done during CPM would alter as the tissue response altered. Positive results would be indicated by a trend and this was seen for patients #3 (actuator 1), #5 (actuator 2 partially), #8 (actuator 2 partially), #9 (actuator 2), #10 (actuator 2) and #12 (actuator 2).

The influences of active finger movement, machine repositioning and 'settling in' affect the form of the force data and a direct correlation between force and finger joint angle data would be impractical.

The following observations are made on the trends in the CPM actuator force data.

#3	MK dig 4 pip - right	barman	Bicycle accident; sustained a palmar cut injury in the skin crease of the PIP joint of the right ring finger; suffered post-traumatic limitation in movement of the DIP joint; arthrolysis of the DIP joint was performed; ideal patient for CPM because after arthrolysis because there is no possibility of further damage. This patient had the best result for CPM treatment, based on the measure of a noticeable reduction in maximum, minimum and mean force magnitudes.
#4	GZ dig 3 pip - right		Smith fracture followed by Sudeck contracture. Noticeable reductions in force standard deviation values.
#5	CDB dig 4 pip - right		Hand was crushed; severe contusion of the right hand with open fracture of the proximal phalanges of the index and ring fingers, the middle phalanx of the ring finger and the distal phalanges of the ring and little fingers. Wire osteosynthesis undertaken; arthrodesis of the little finger DIP and arthrolysis of the ring and little finger PIPs; tendolysis of ring finger PIP; un-united fracture bone in ring finger replaced with fresh bone. Obvious trends in maximum compressive force values.
#6	AM digs 3, 4 and 5 pip - right	machine operator	Traumatic lesion of the flexor tendons to the middle, ring and little fingers in the areas of the proximal phalanges. Primary tendon repair performed; followed by Kleinert traction therapy; tendolyses on the flexor tendons of the middle, ring and little fingers and an arthrolysis of the little finger DIP performed to relieve flexion contractures; hard tissue scars remained on the palmar surfaces of the injured fingers in the region of the injuries on the proximal phalanges. The positive effects of the machine working hard to reduce standard deviation values were shown for the second actuator. Other effects were minimal.

continued/

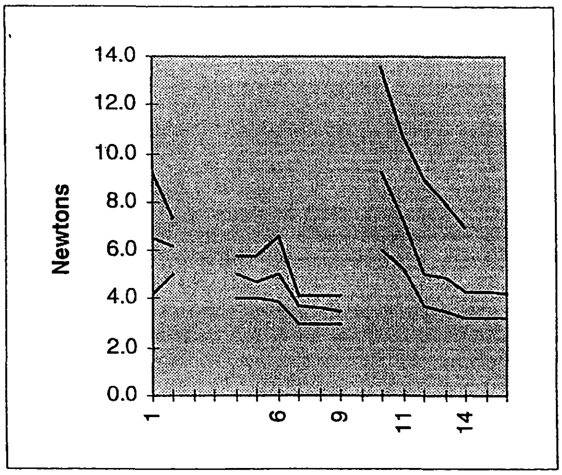
#7	CM digs 4 & 5 pip - left	child minder	Attempted to commit suicide by cutting the left wrist and left elbow; complete lesions of all superficial and deep tendons, the ulnar & median nerves, as well as the arteria ulnaris; nerves (from the foot) were transplanted into the hand.; neurolyses of the median & ulnar nerves and tendolyses of all deep tendons and the flexor pollicis longus. Trends in maximum, minimum and mean force values for actuator 2 are clear to observe.
#8	IS digs 2 & 3 mcp - left		Clear trends available for the second actuator.
#9	GE digs 2 & 4 pip - right		Clear trends available for the first actuator.
#10	RV dig 2 pip and dip - left		Crush injury but no fracture to the index finger; after the injury, there was a lack of movement of the PIP and DIP joints; at the time of CPM treatment, the finger was swollen, the skin a little red and sensibility was a little diminished. Clear trends available for the second actuator.
#12	EP dig 5 pip - left		No trends evident.
#13	Ma digs 2 & 5 pip - left		Clear trends available for both actuators.
#14	Ha digs 2 & 3 pip - left		Trends are partially available for both actuators

Trends in CPM actuator force data – all Berlin patients
table 7.7

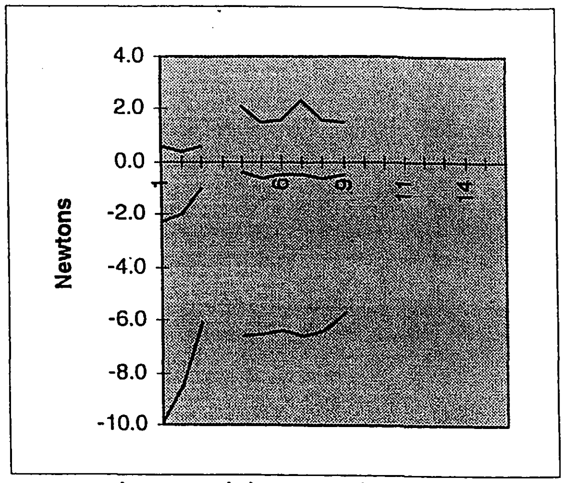
A summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value, for the Berlin patients, is provided in figure 7.15, on the next thirteen pages. The interpretation of these plots is provided in chapter 8.

patient #3 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

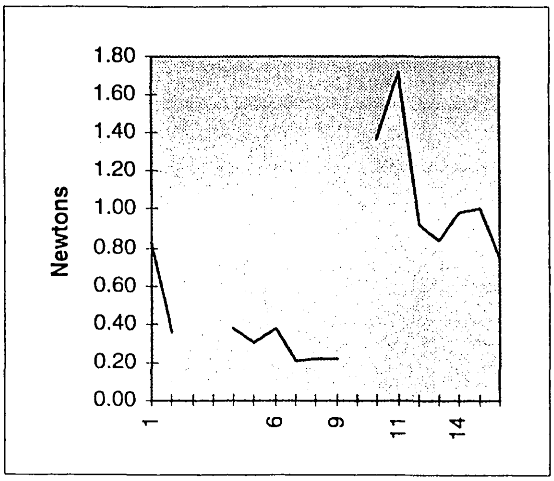
ACTUATOR 1 | **ACTUATOR 2**



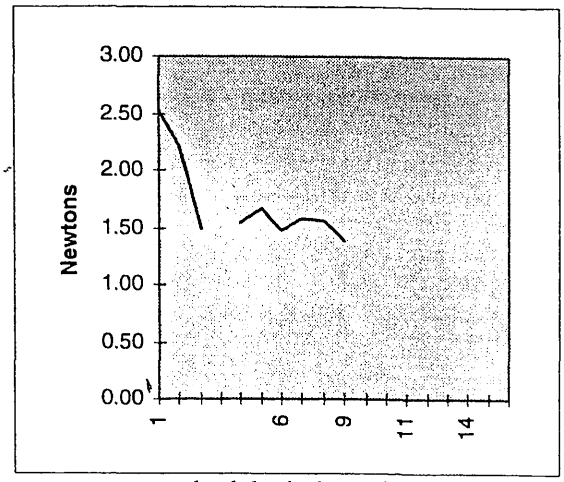
maximum, minimum and mean force magnitudes



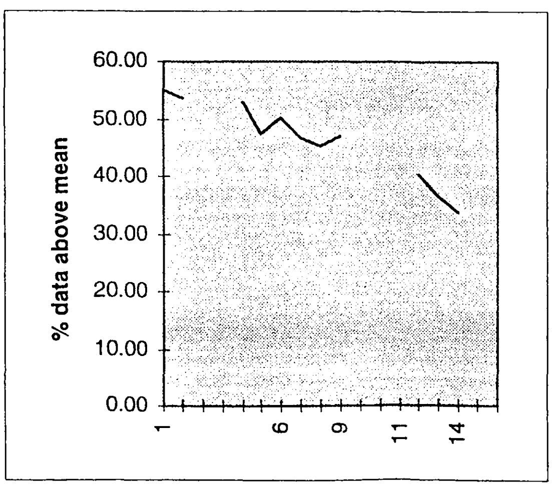
maximum, minimum and mean force magnitudes



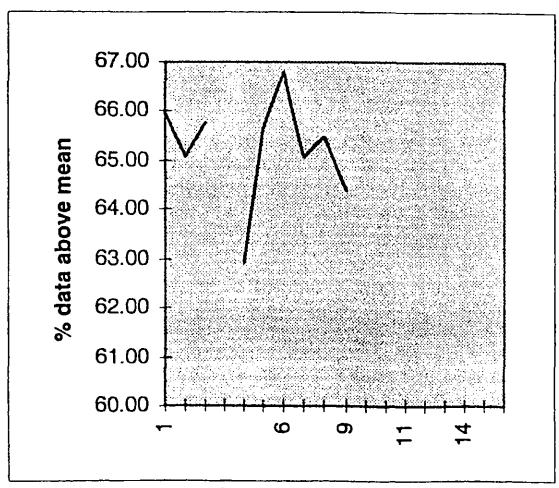
standard deviation - force



standard deviation - force



percentage of data above mean value

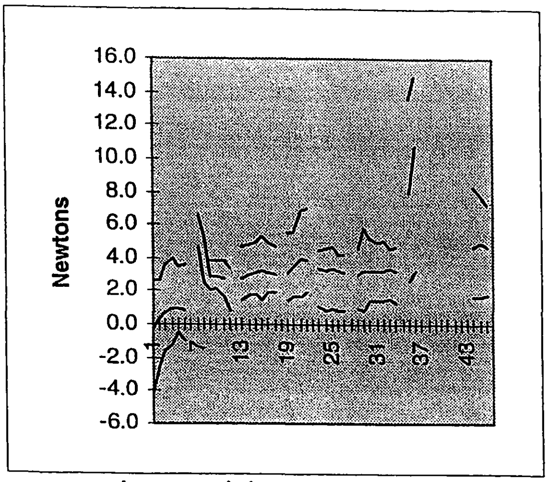


percentage of data above mean value

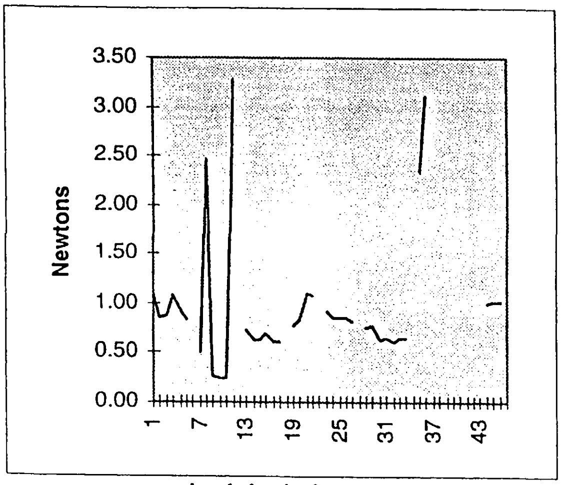
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 1/13 pages

patient #4 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

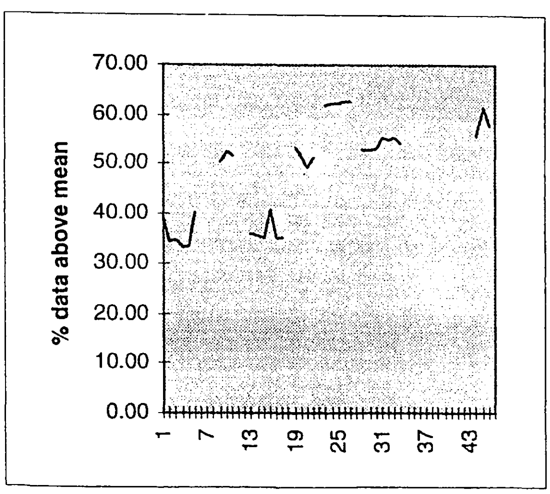
ACTUATOR 1



maximum, minimum and mean force magnitudes

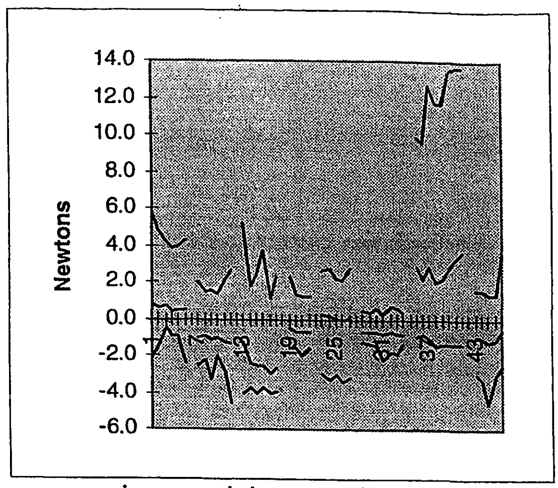


standard deviation - force

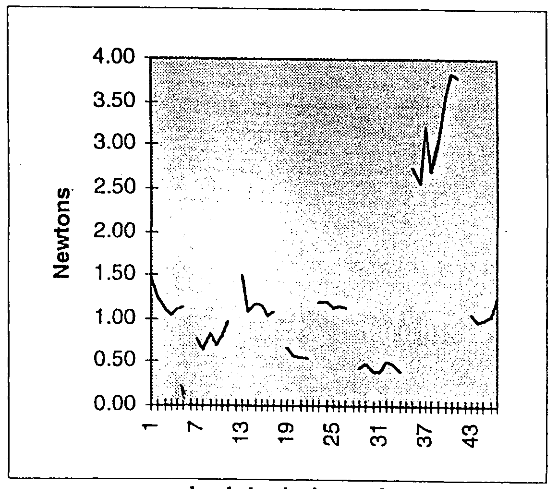


percentage of data above mean value

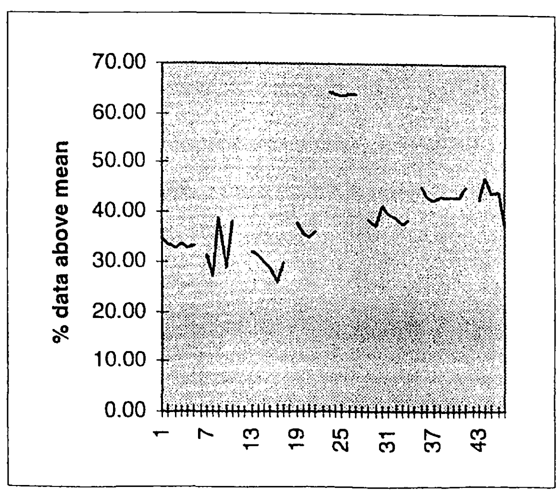
ACTUATOR 2



maximum, minimum and mean force magnitudes



standard deviation - force



percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 2/13 pages

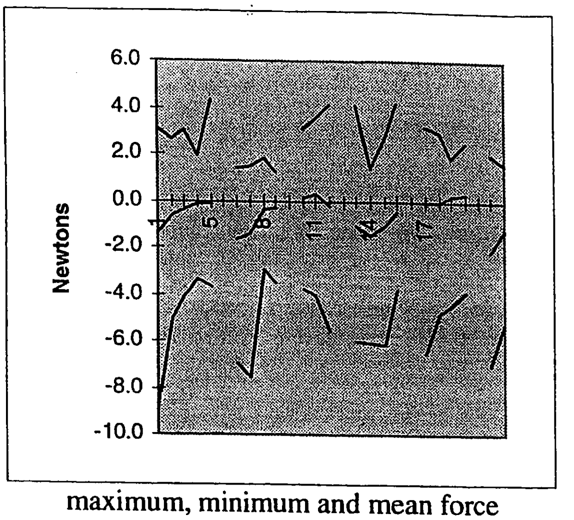
patient #5

Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

ACTUATOR 1

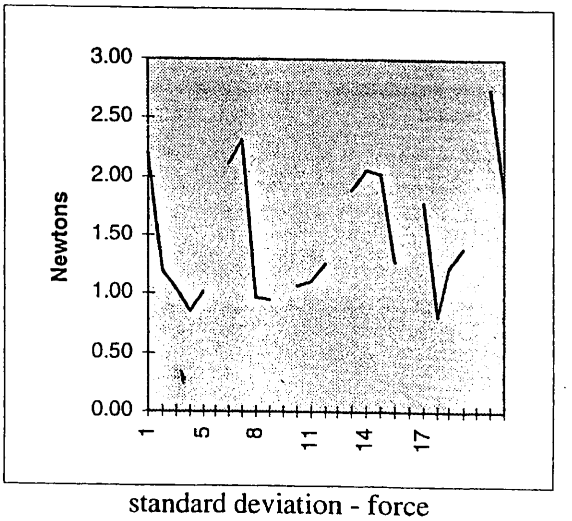
ACTUATOR 2

no data available



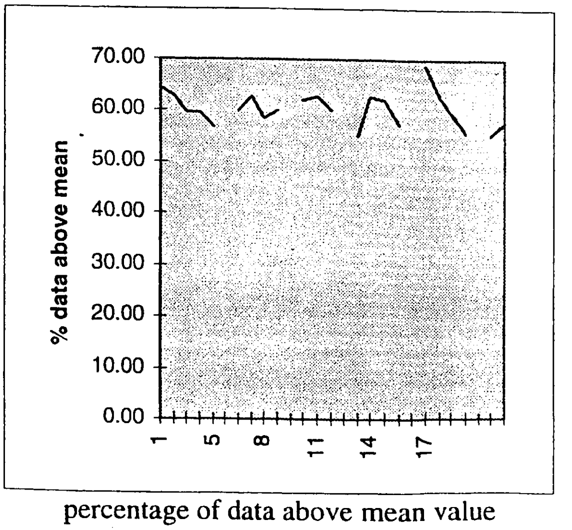
maximum, minimum and mean force magnitudes

no data available



standard deviation - force

no data available



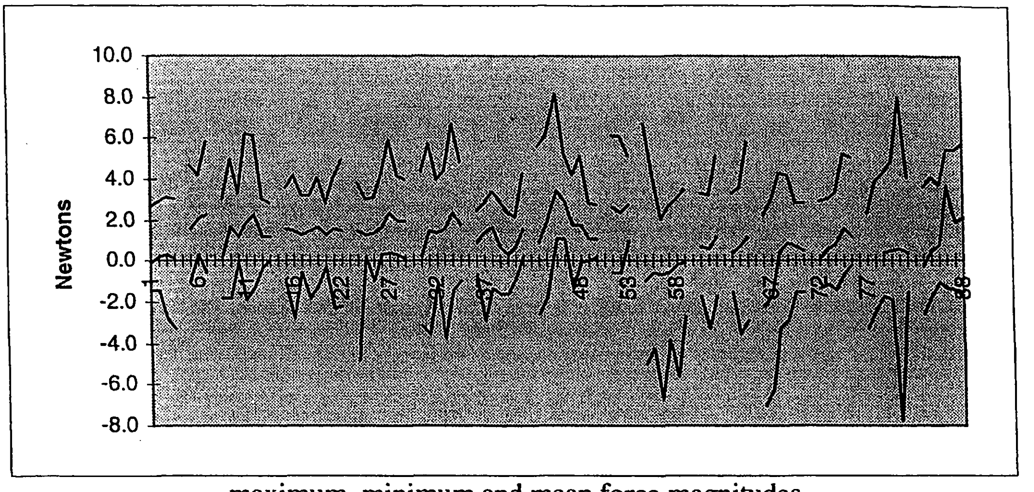
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients

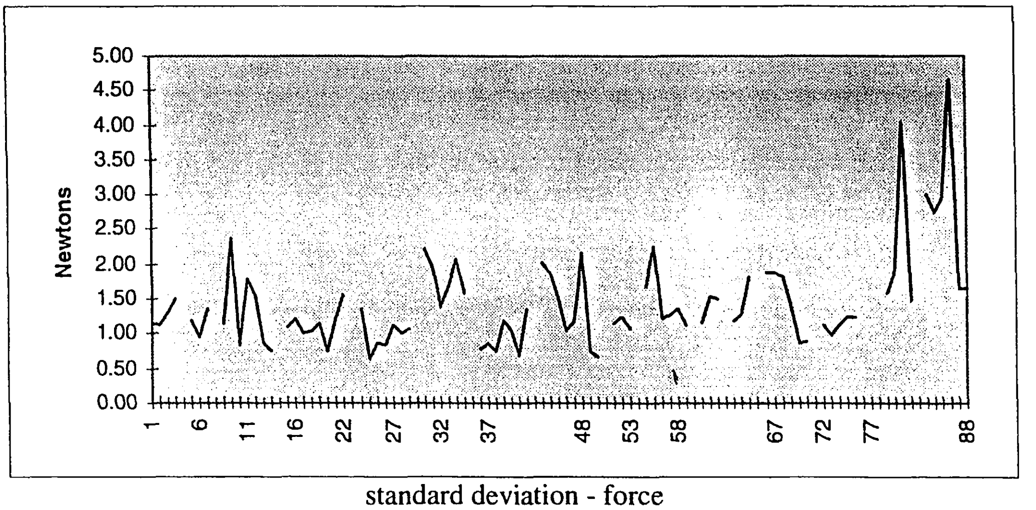
figure 7.15 – 3/13 pages

patient #6 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

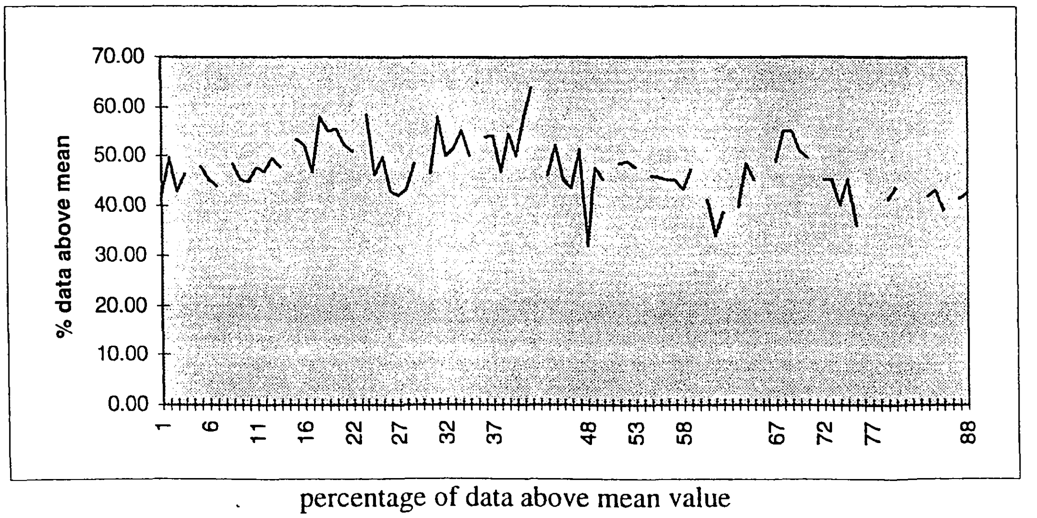
ACTUATOR 1



maximum, minimum and mean force magnitudes



standard deviation - force



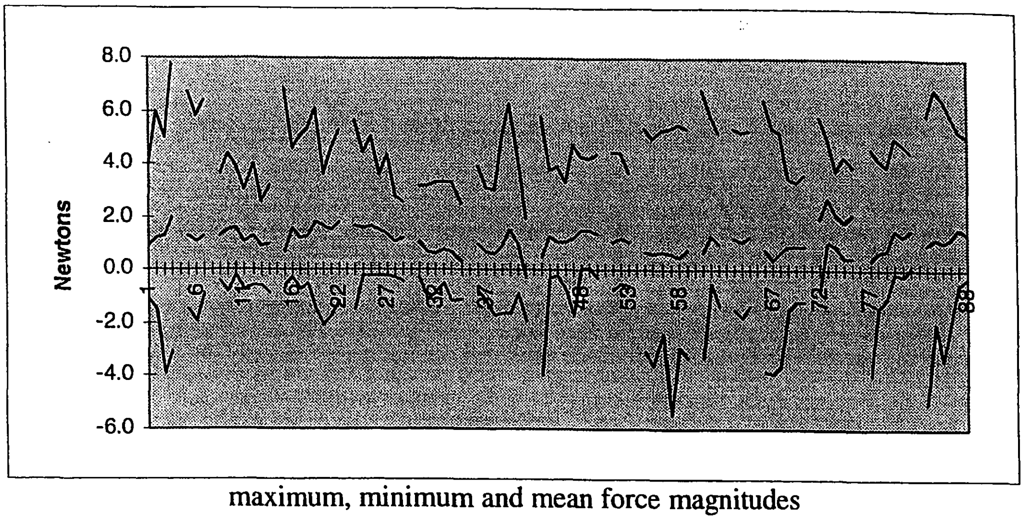
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standar deviation and percentage of data above mean value for the Berlin patients

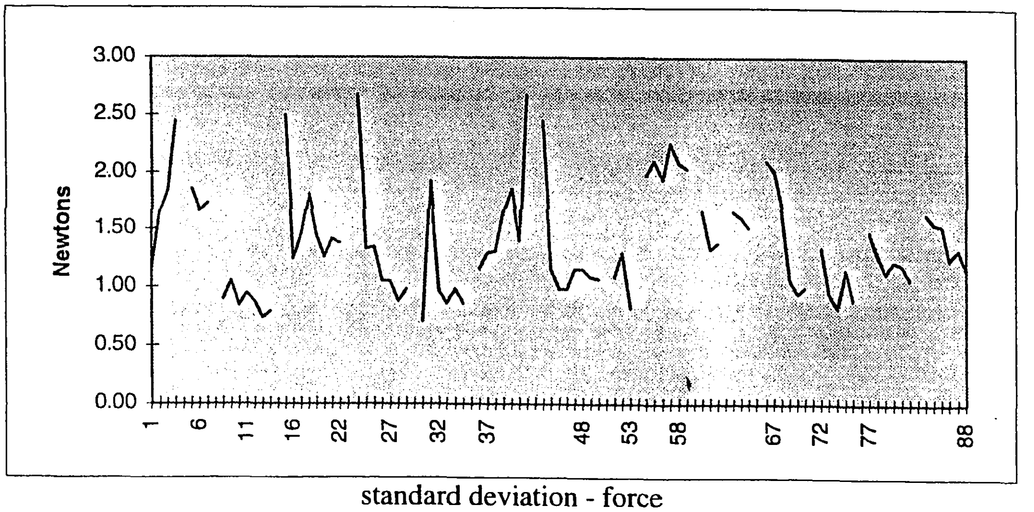
figure 7.15 – 4/13 pages

patient #6 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

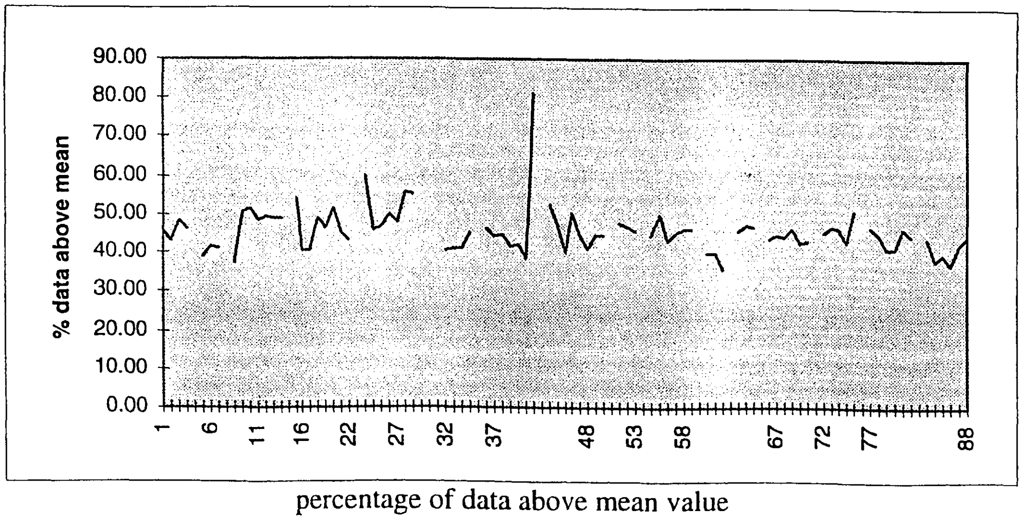
ACTUATOR 2



maximum, minimum and mean force magnitudes



standard deviation - force

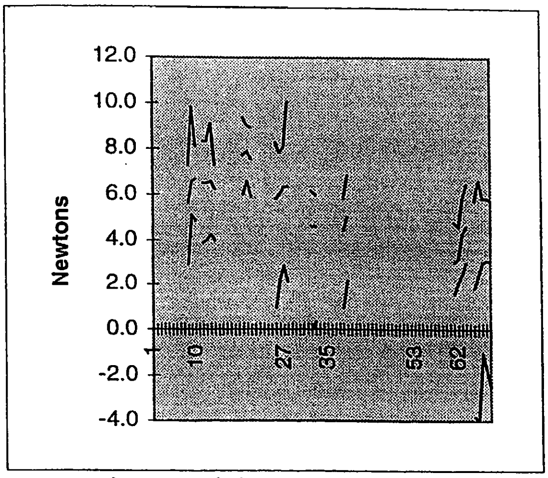


percentage of data above mean value

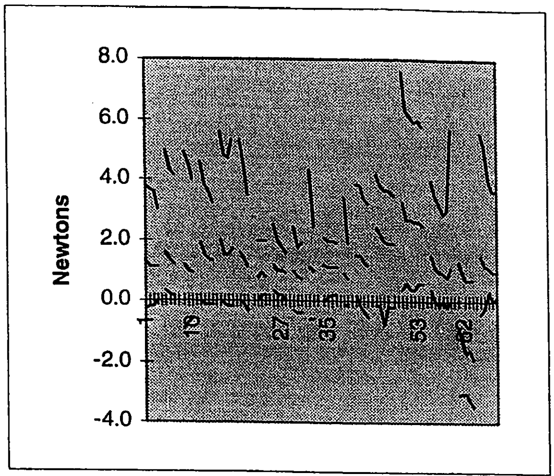
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 5/13 pages

patient #7 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

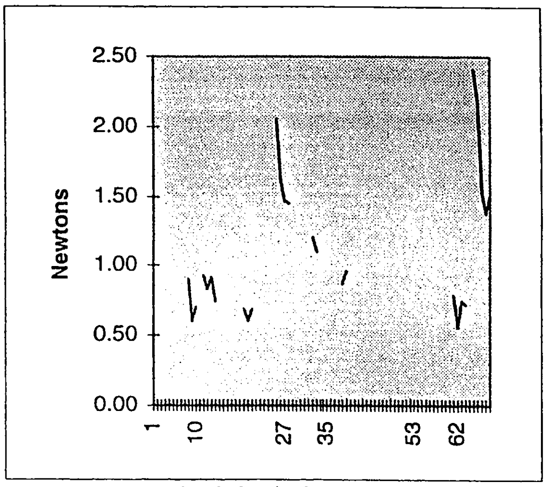
ACTUATOR 1 **ACTUATOR 2**



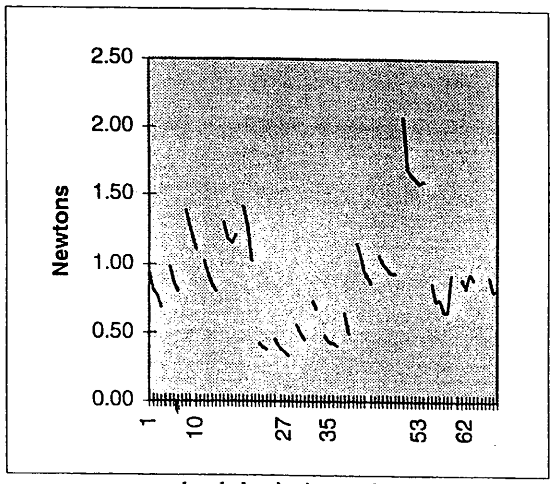
maximum, minimum and mean force magnitudes



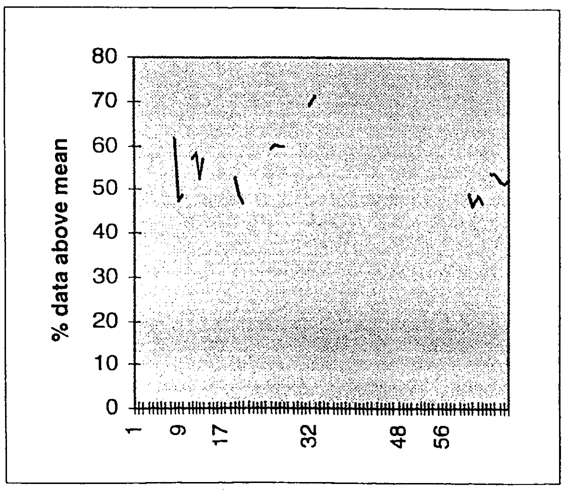
maximum, minimum and mean force magnitudes



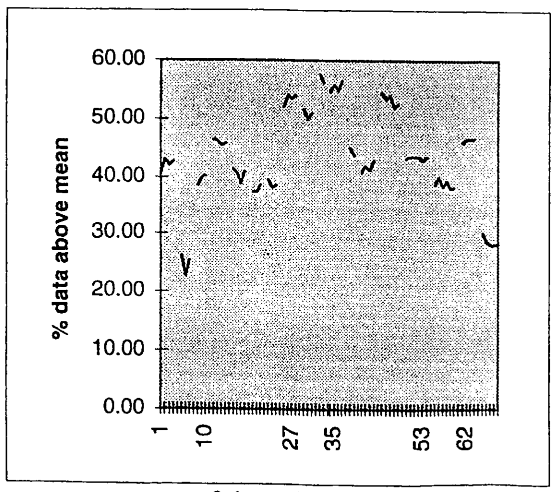
standard deviation - force



standard deviation - force



percentage of data above mean value



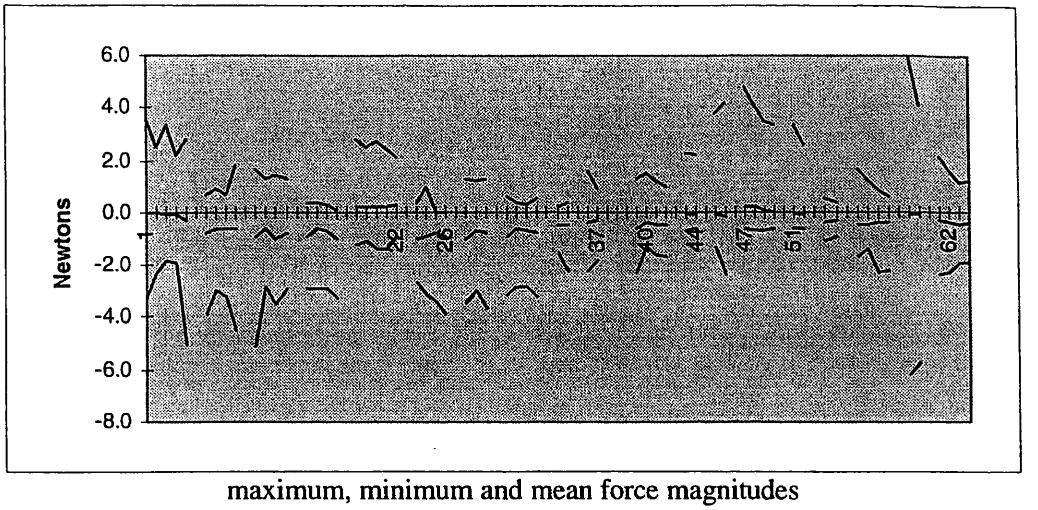
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients

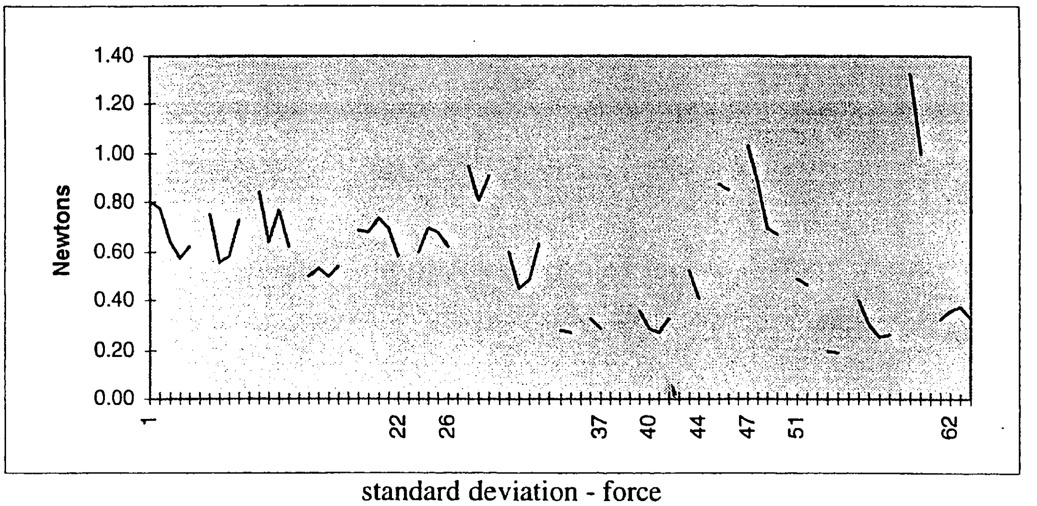
figure 7.15 – 6/ 13 pages

patient #8 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

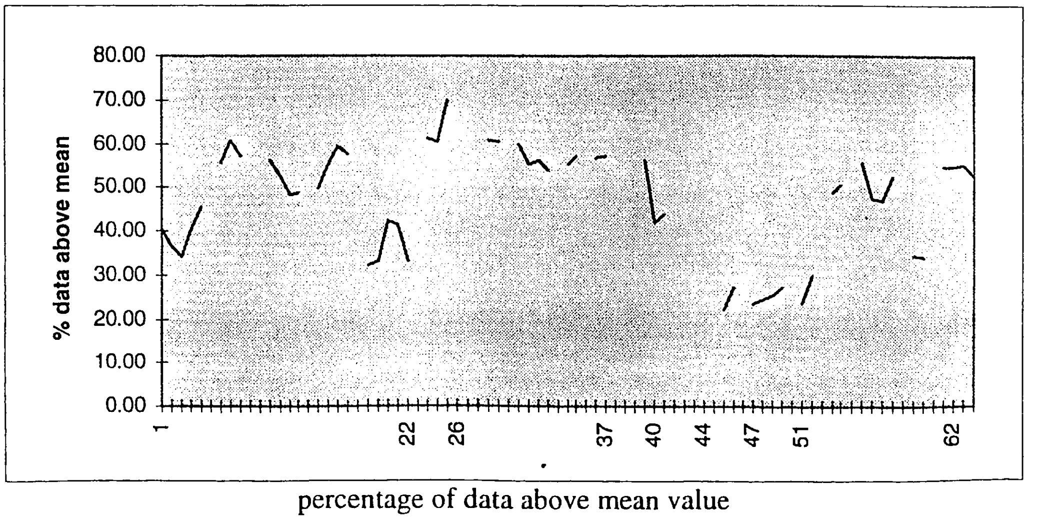
ACTUATOR 1



maximum, minimum and mean force magnitudes



standard deviation - force



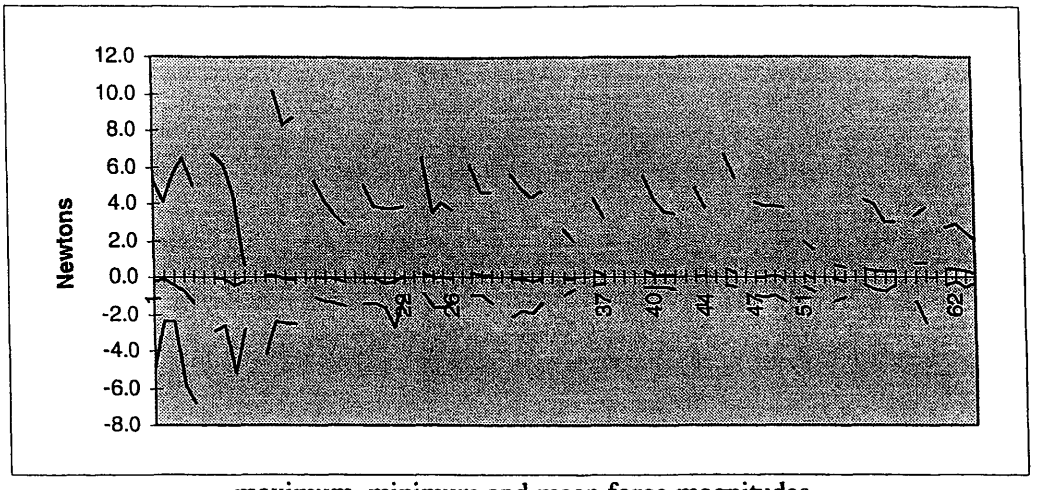
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 7/13 pages

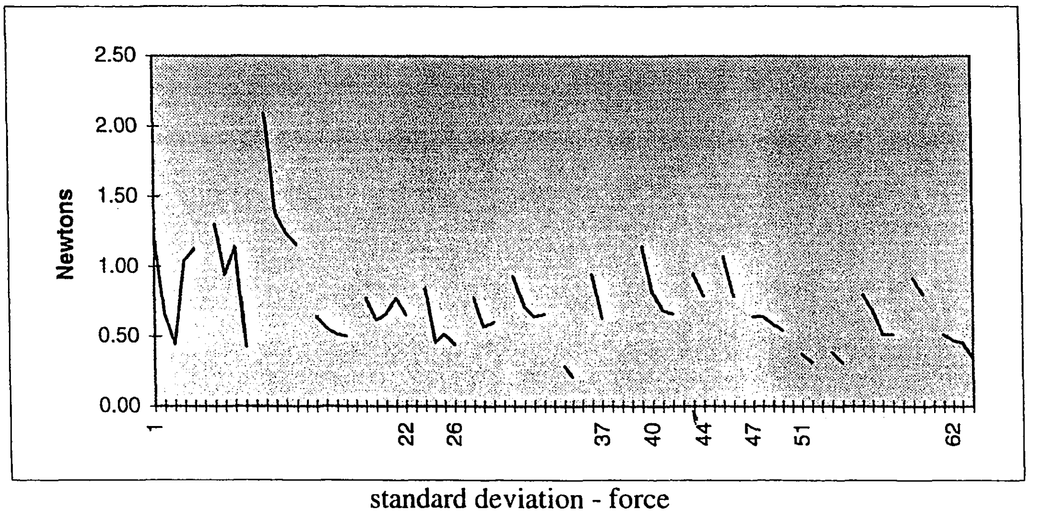
Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

patient #8

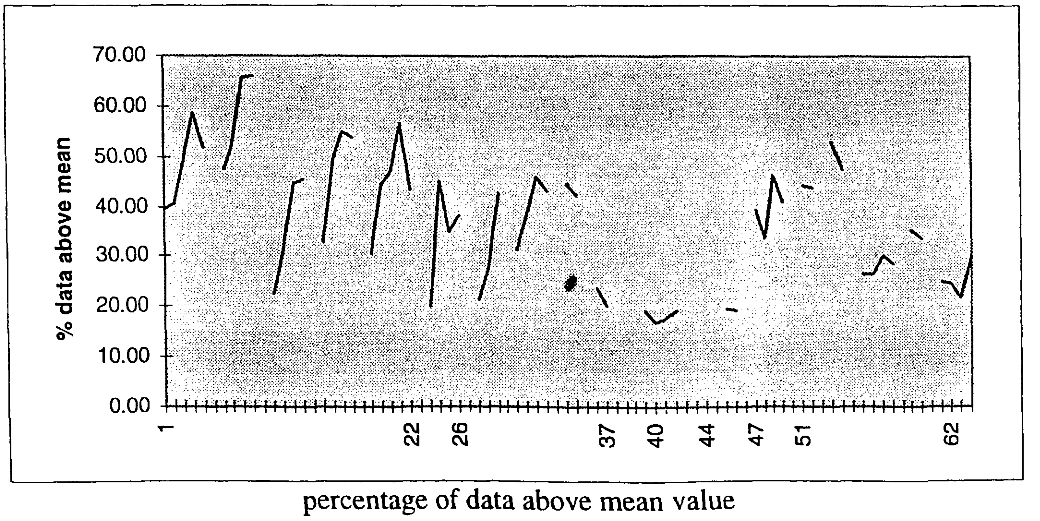
ACTUATOR 2



maximum, minimum and mean force magnitudes



standard deviation - force

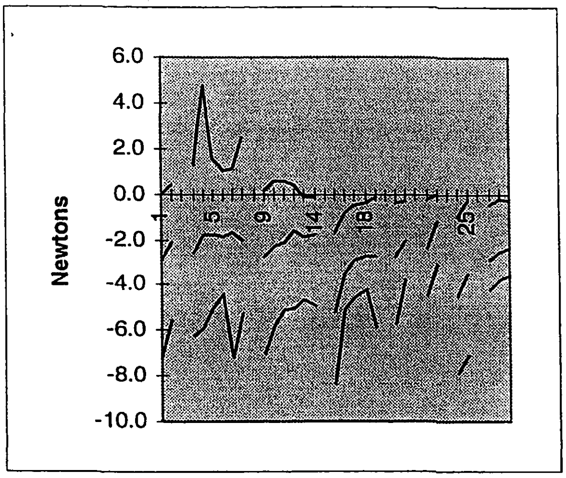


percentage of data above mean value

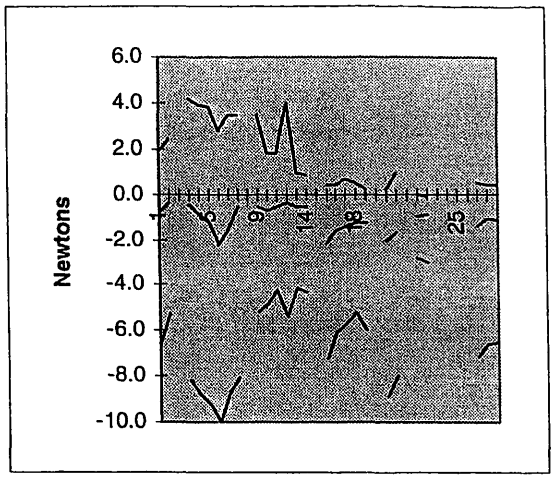
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 8/13 pages

patient #9 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

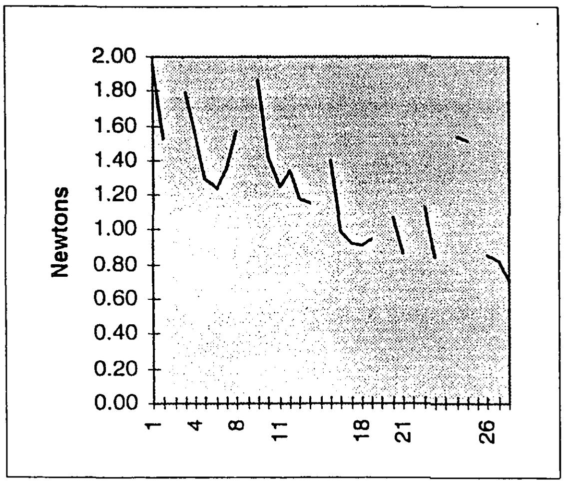
ACTUATOR 1 | **ACTUATOR 2**



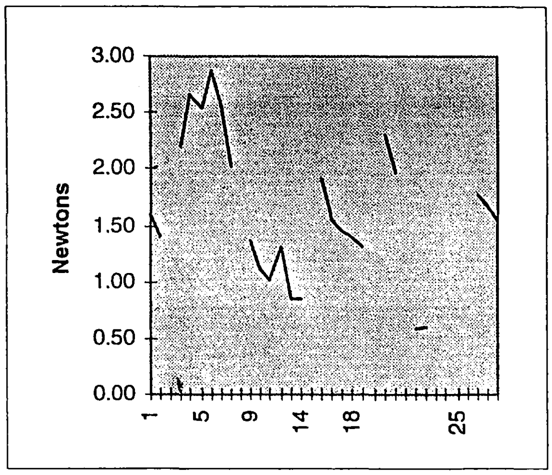
maximum, minimum and mean force magnitudes



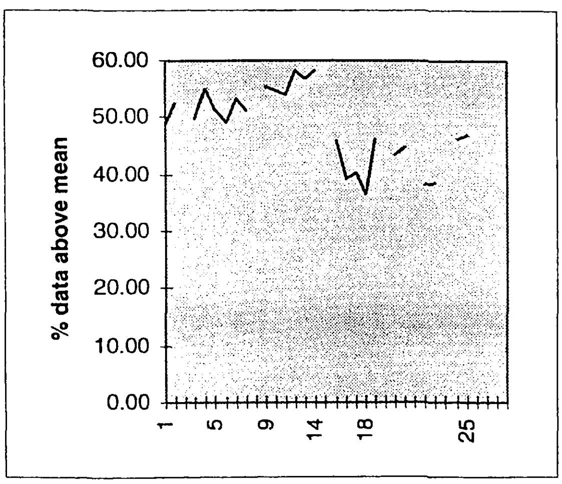
maximum, minimum and mean force magnitudes



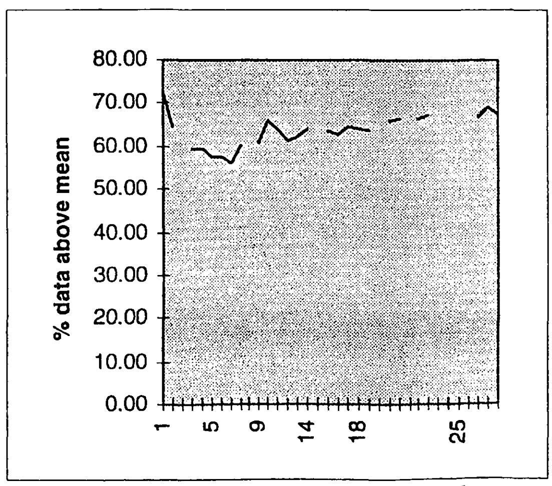
standard deviation - force



standard deviation - force



percentage of data above mean value

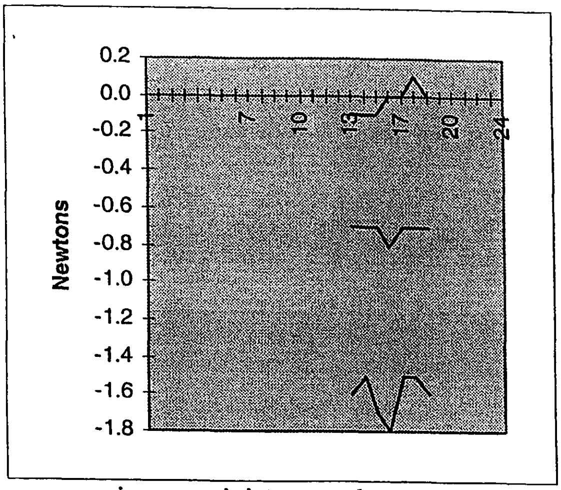


percentage of data above mean value

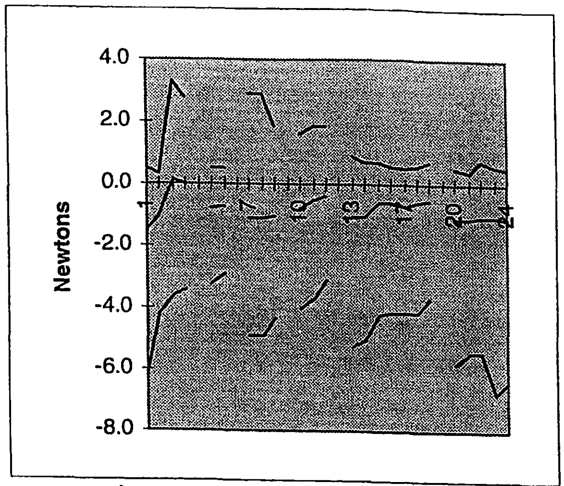
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 9/13 pages

patient #10 Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

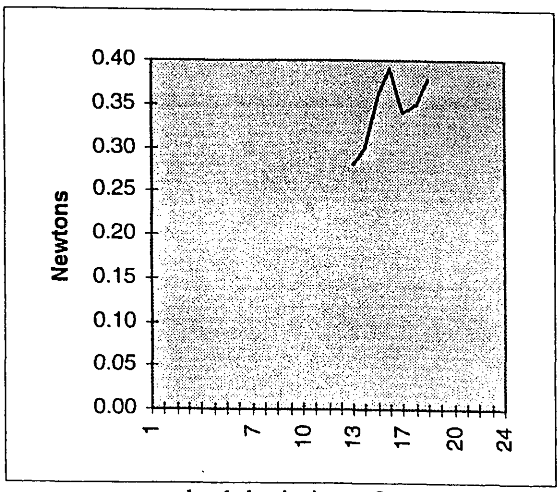
ACTUATOR 1 | **ACTUATOR 2**



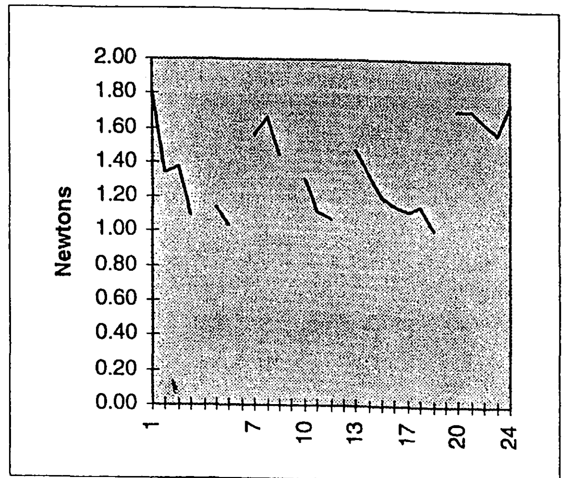
maximum, minimum and mean force magnitudes



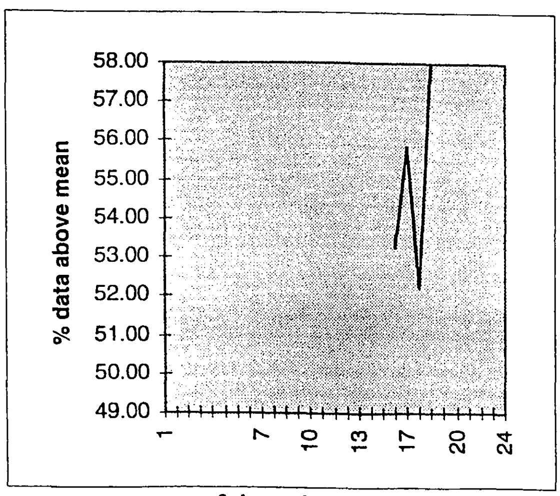
maximum, minimum and mean force magnitudes



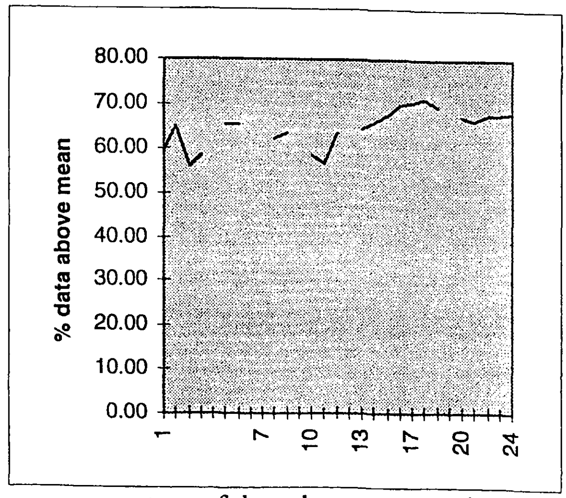
standard deviation - force



standard deviation - force



percentage of data above mean value



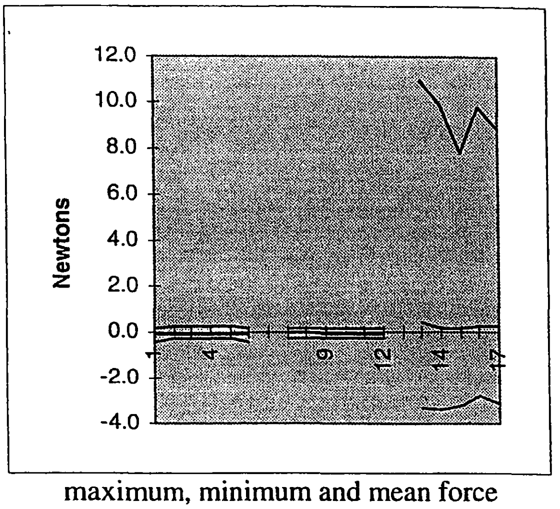
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients
figure 7.15 – 10/13 pages

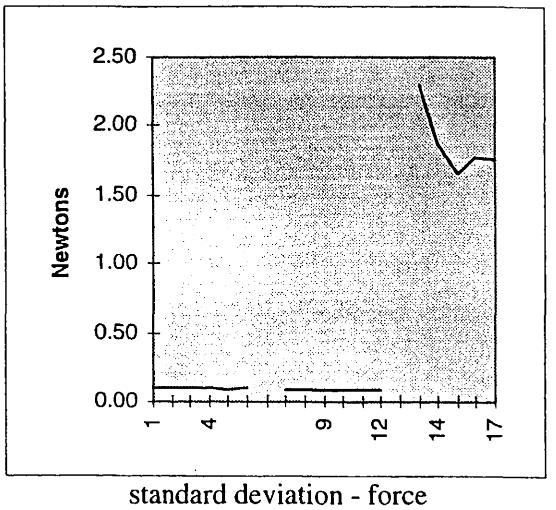
patient #12

Each continuous line represents a treatment session, comprising a series of five minute cycli movements between two minute pause periods (plots of data taken from appendix 5.5)

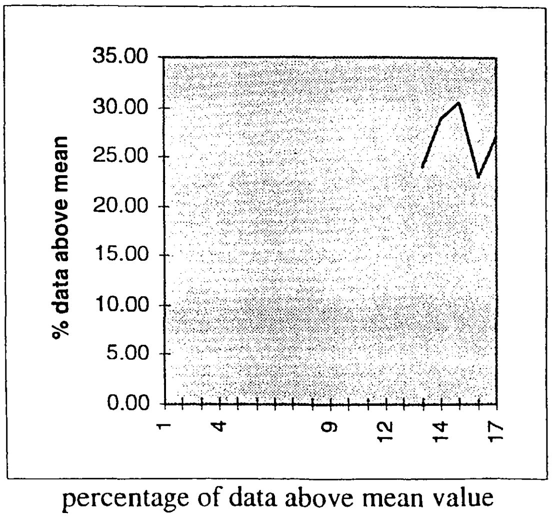
ACTUATOR 1



maximum, minimum and mean force magnitudes

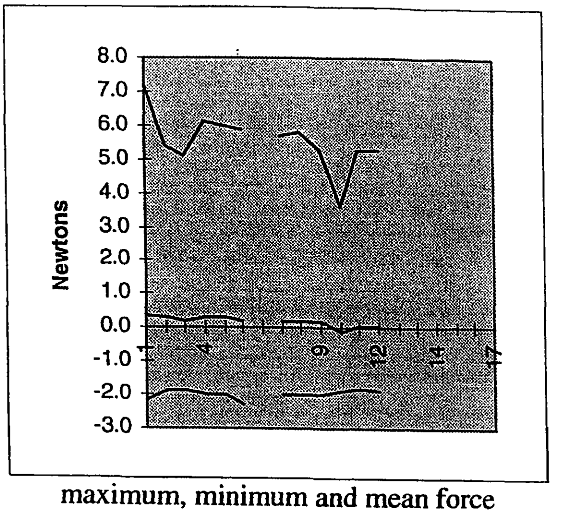


standard deviation - force

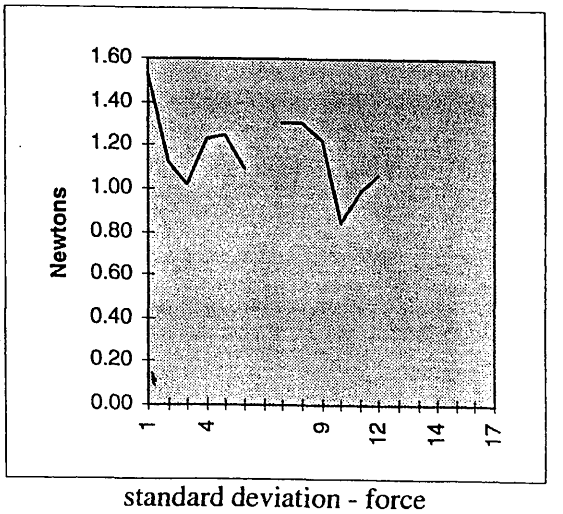


percentage of data above mean value

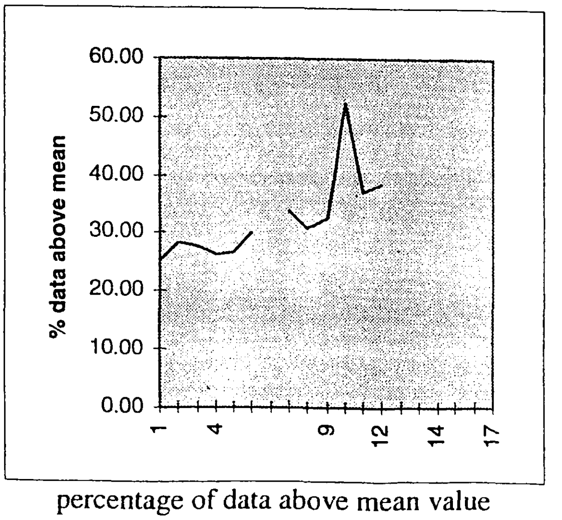
ACTUATOR 2



maximum, minimum and mean force magnitudes



standard deviation - force



percentage of data above mean value

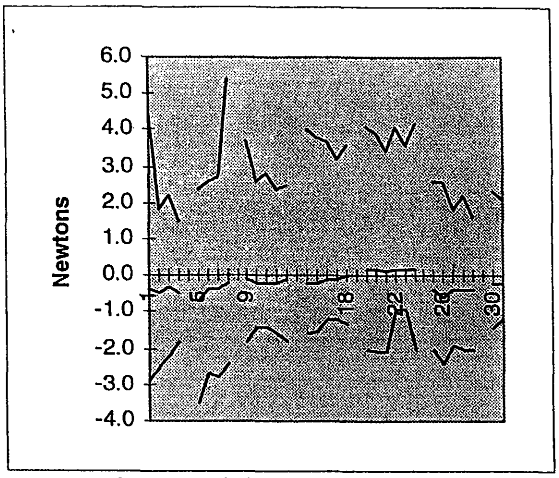
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients

figure 7.15 – 11/13 pages

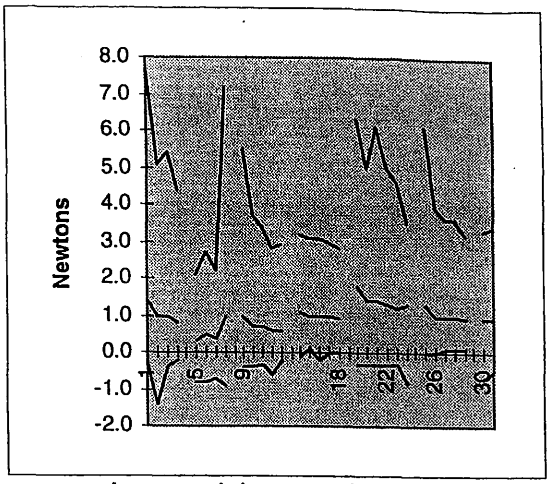
patient #13

Each continuous line represents a treatment session, comprising a series of five minute cyclic movements between two minute pause periods (plots of data taken from appendix 5.5)

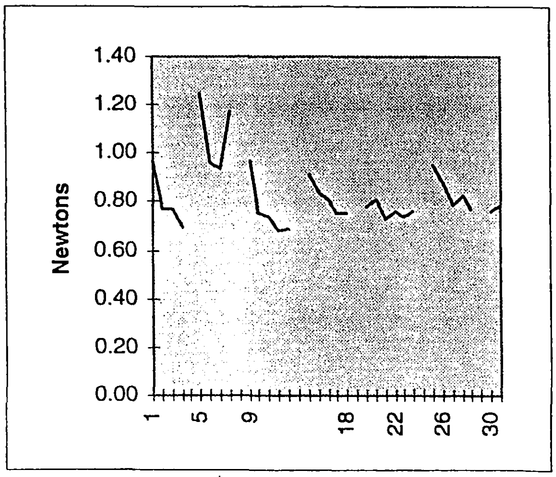
ACTUATOR 1 | **ACTUATOR 2**



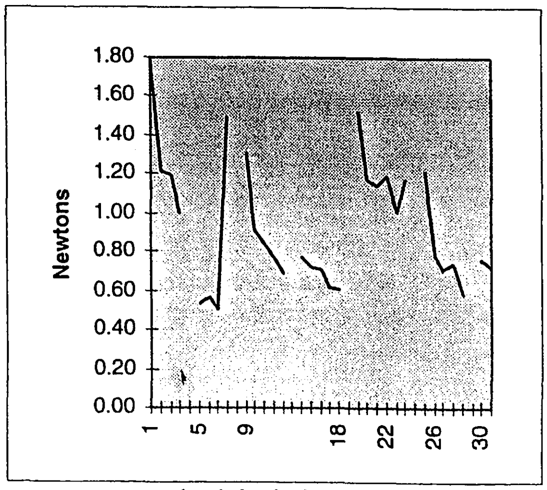
maximum, minimum and mean force magnitudes



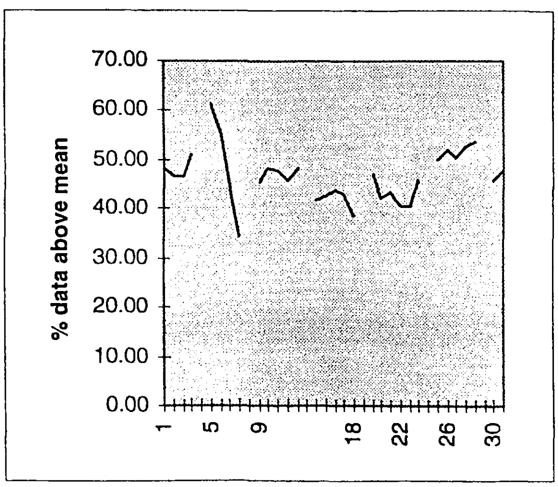
maximum, minimum and mean force magnitudes



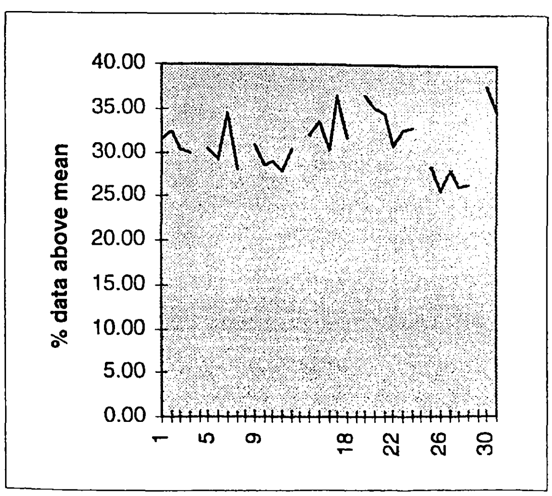
standard deviation - force



standard deviation - force



percentage of data above mean value



percentage of data above mean value

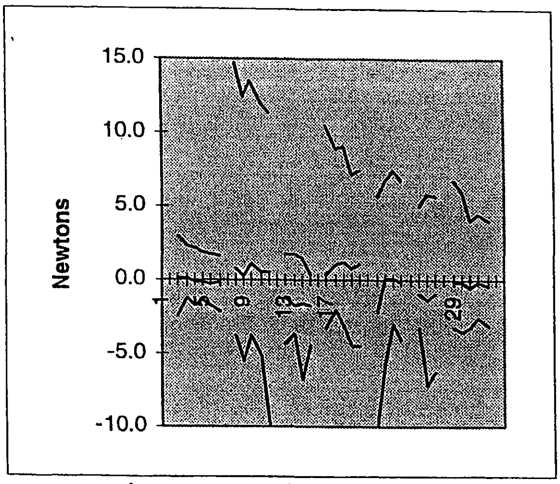
Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients

figure 7.15 – 12/13 pages

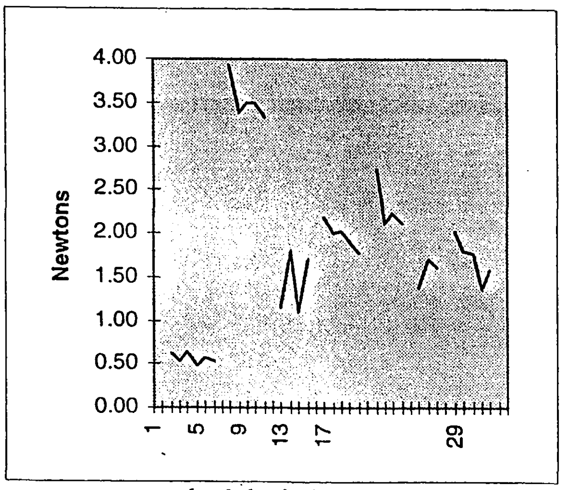
patient #14

Each continuous line represents a treatment session, comprising a series of five minute cycli movements between two minute pause periods (plots of data taken from appendix 5.5)

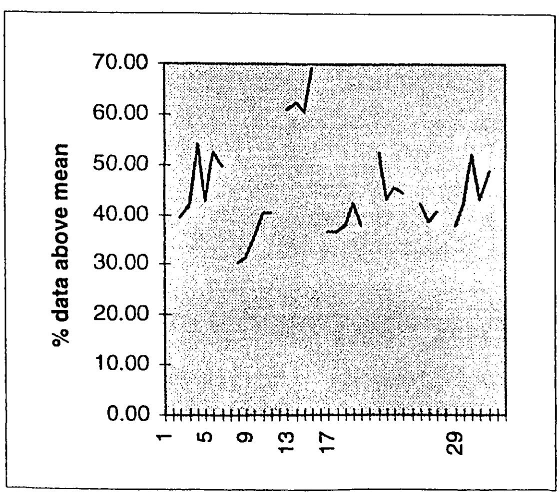
ACTUATOR 1



maximum, mean & minimum force magnitudes

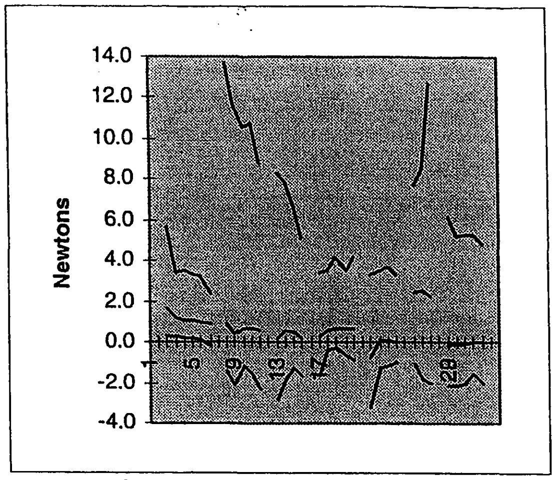


standard deviation - force

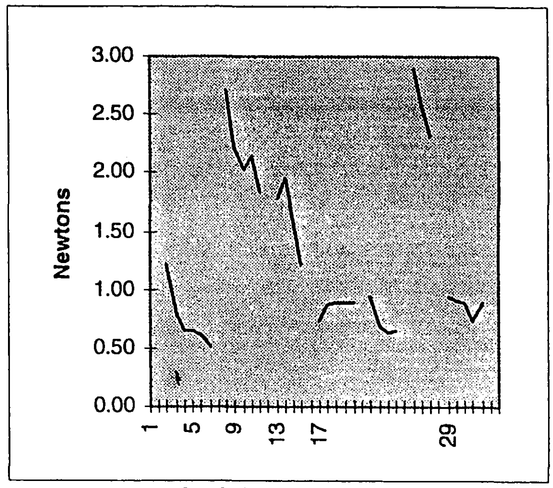


percentage of data above mean value

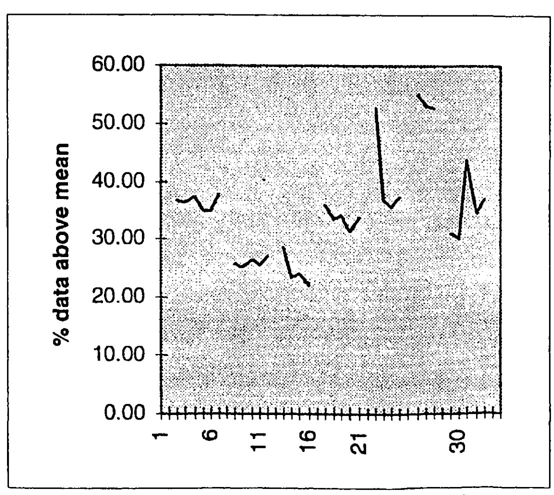
ACTUATOR 2



maximum, mean & minimum force magnitudes



standard deviation - force



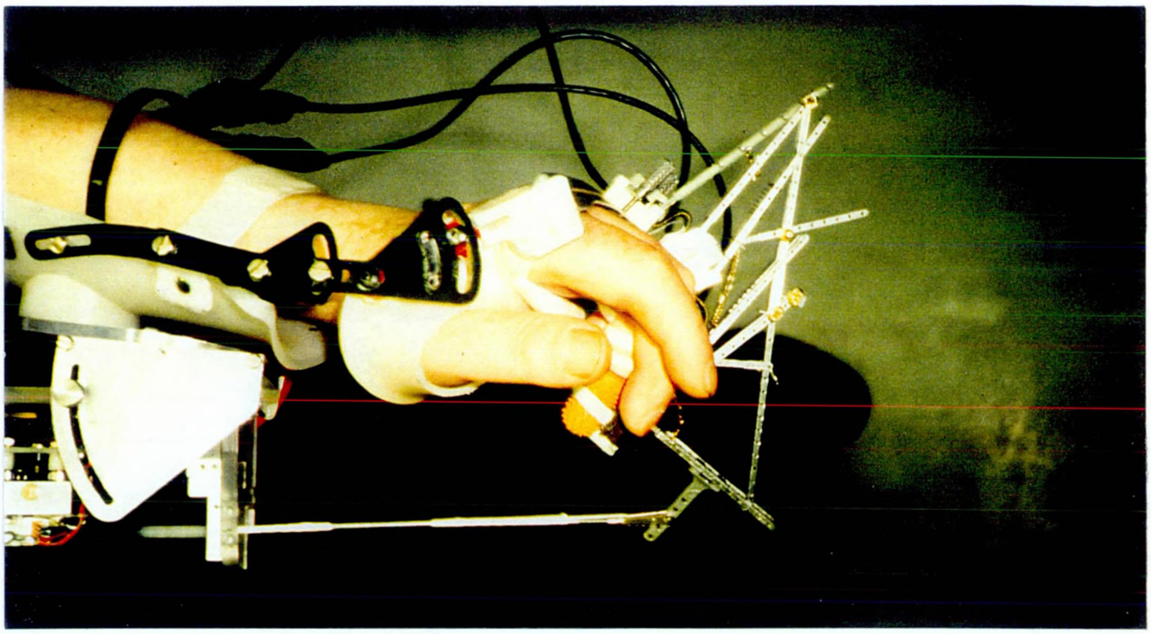
percentage of data above mean value

Summary of the variations in maximum, minimum and mean force magnitudes, standard deviation and percentage of data above mean value for the Berlin patients

figure 7.15 – 13/13 pages

7.3 Improvements to the finger linkage mechanism

The finger linkage was successfully used in the clinical trials conducted with the Dundee CPM machine but patients and clinical practitioners were critical of its size and its poor cosmesis (see figure 7.16).



Finger linkage applied to a Dundee patient
Figure 7.16

The analysis of its kinematic behaviour (section 5.5, page 114) was continued to both reduce its size and to remove the spring in link *n7n8* (figure 5.24, page 133). The optimisation process of satisfying these goals and ensuring the finger joints could be moved through their full range of motion was hampered by the non-linear relationships in the mathematical expressions to define the finger joint angles. These expressions contained both the lengths of the links and the crank angles (appendix 3.2). For instance, the simplest joint angle to optimise is the MCP joint which can be determined from the x, y coordinate values of nodes *n*1, *n*2 and *n*6. The MCP joint angle is;

$$\cos(\text{alphaMCP}) = \frac{[(X6G-X2G) * (X1G-X2G)] + [(Y6G-Y2G) * (Y1G-Y2G)]}{(D26*D12)}$$

The coordinate positions of nodes $n1$ and $n2$ are fixed in the metacarpal axis system so the expression above can be rewritten using the lengths of the links;

cos (alphaMCP) =

[(D26*((D67^2+D57^2+2*D57*D26-2*D57^2-D26^2-
D25^2)/(2*D57*D25-2*D26*D25))*cos(atan((Y5G-
Y2G)/(X5G-X2G)))-D26*sin(acos((D67^2+D57^2
+2*D57*D26-2*D57^2-D26^2-D25^2)/(2*D57*
D25-2*D26*D25)))*sin(atan((Y5G-Y2G)/(X5G-X2G))))] * (X1G-X2G)]

―――――――――――――――――――――――――――――――

(D26*D12)

+

[(D26*((D67^2+D57^2+2*D57*D26-2*D57^2-D26^2-
D25^2)/(2*D57*D25-2*D26*D25))*sin(atan((Y5G-
Y2G)/(X5G-X2G)))+D26*sin(acos((D67^2+D57^2+2
*D57*D26-2*D57^2-D26^2-D25^2)/(2*D57*D25-
2*D26*D25)))*cos(atan((Y5G-Y2G)/(X5G-X2G)))) * (Y1G-Y2G)]

―――――――――――――――――――――――――――――――

(D26*D12)

Although complicated, this expression is not as complicated as those for the PIP and DIP joints, which are situated more distally in the kinematic chain. It can be seen that optimisation process of the linkage design, by a numerical approach, would have a doubtful success. Indeed, a solution might not actually exist!

Conventional matrix methods were inappropriate so a program *opt.for* was written to find a solution by a series of 'trial and error' steps. A flow chart describing the program's construction is shown in appendix 3.3 and the program listing is given in appendix 3.4. The program initially set all link lengths to minimum values and increased the length of each one, in turn, by a given amount. For each increase, the crank is moved through its full range and the subsequent finger joint angles are compared against the target values.

Both a partial solution (for the MCP and PIP joints only) and a full solution (for all three joints) were investigated. The program is a 'hit or miss' type and has the severe disadvantage that it requires a protracted period to run. Its use therefore depended upon constant intervention to adjust the targets in the iteration loops.

A solution was found for the MCP and PIP joints but because of difficulties encountered in coordinating their movements with the movement of the DIP joint, the solution could not be extended to the DIP joint. The solution is illustrated as *case A* in figure 7.17 *(finger11.mdx)*. The lengths of the links for *case A* are given in table 7.8;

*n*3*n*4	*n*4*n*5	*n*2*n*5	*n*4*n*8	*n*8*n*9	*n*9*n*10	*n*12*n*13	*n*7*n*8	*n*6*n*7	*n*6*n*10	*n*9*n*13
44.725	32.843	30.269	8.157	33.33	38.93	29.109	40.017	21.284	18.967	44.815

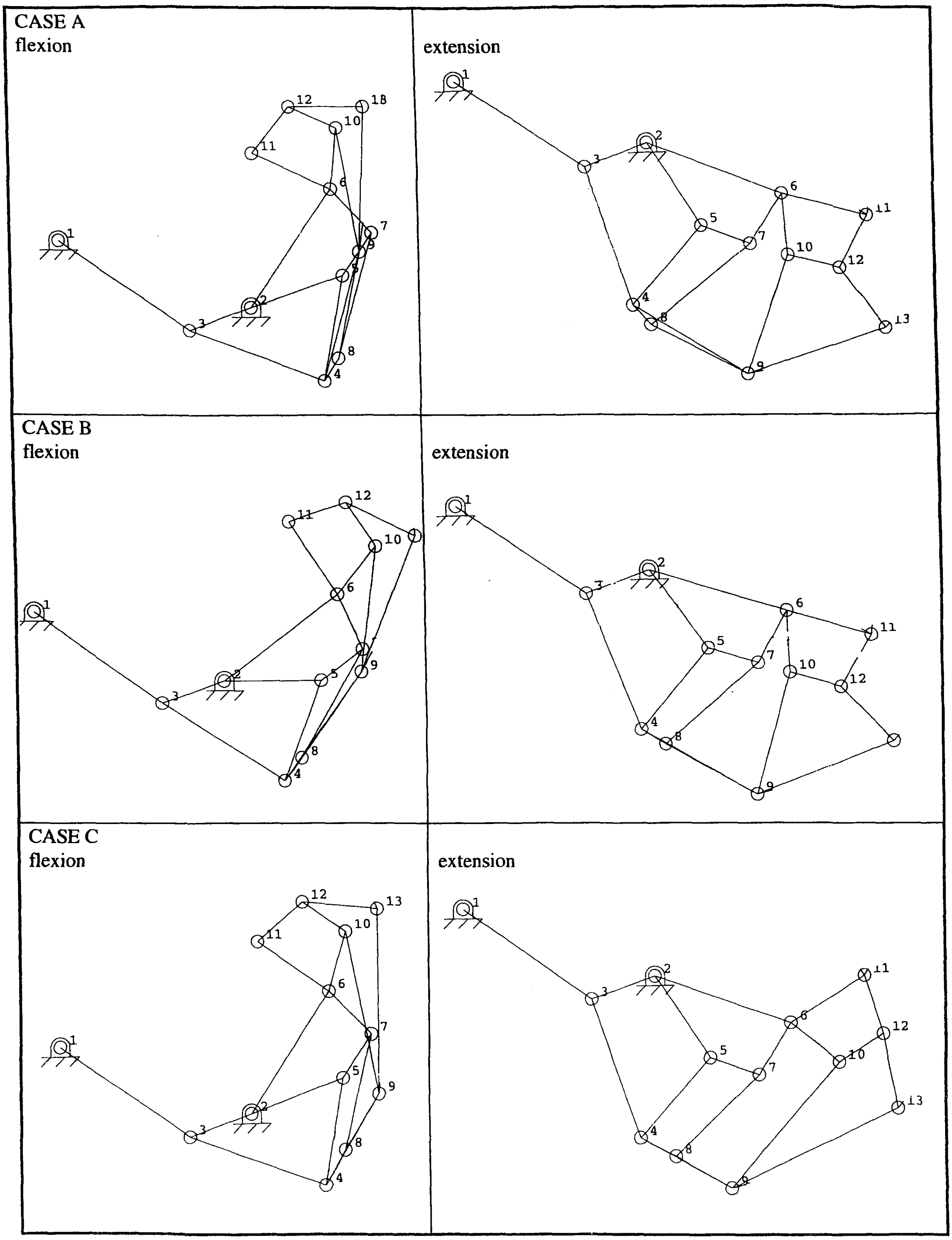
Lengths of links for optimised finger linkage
table 7.8

However, the kinematic behaviour of the linkage is extremely sensitive to node positions and this is illustrated for *case B* and *case C* in table 7.9

	LINK: crank	MCP joint			PIP joint		MCP joint		PIP joint	
case	*n*3*n*4	*n*4*n*8	*n*8*n*7	*n*4*n*5	*n*8*n*9	*n*9*n*10	flex	ext	flex	ext
A	44.725	8.157	40.017	32.843	33.33	38.93	74	0	100	5
B	44.725	8.783	40.017	32.843	32.297	38.93	56	2	85	0
C	44.725	12.224	36.126	32.843	19.88	50.582	75	0	86	52

Sensitivity of kinematic behaviour of optimised linkage for different link lengths
table 7.9

Case A is the best case and *cases B* and *C* are progressively worse. *Case A* represents the best case because it provides good flexion of the MCP and PIP joints and only a five-degree lag in PIP extension. *Case B* provides full extension of the PIP joint but only at the expense of reducing the maximum flexion angles of both the MCP and PIP joints. *Case C* attempts to restore the flexion capability of the MCP joint but at the considerable expense of severely limiting PIP extension to fifty two degrees. Comparison of *case B* with *case A* reveals that a trivial adjustment of the coordinates of node *n*8 severely affects the maximum flexion angle of the MCP joint. The maximum flexion angle of the PIP joint is also affected, though adjustment of node *n*9 makes some, but not full, correction. Comparison of *case C* with *case A* shows that a further adjustment of node *n*8 can restore the maximum flexion angle of the MCP joint but adjustment of node *n*9 cannot correct the severe reduction in the maximum extension angle of the PIP joint.



Optimised linkage design (case A) and its sensitivity to different lengths of internal links (cases B and C)
figure 7.17

CHAPTER 8

CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

8.1.1 Introduction

Discussions were held with clinicians and therapists, prior to the start of this research, to identify a suitable topic for investigation in the general area of hand rehabilitation. It was agreed that research into continuous passive motion therapy (CPM) hand therapy would be worthwhile because;

(i) it would provide data on the magnitudes of forces encountered during hand CPM

(ii) knowledge would be acquired on its effect for increasing finger joint range of motion for typical finger joint disorders, *and*

(iii) the practical difficulties of applying hand CPM would be identified and ideally resolved before CPM could be advocated for rehabilitation after flexor tendon repairs.

The aims of the research were;

(i) to study the effect of CPM upon finger joints with limited range of motion (ROM);

(ii) to investigate the development of a prototype CPM machine for the rehabilitation of flexor tendon repairs

The achievement of the second aim would require the use of the practical knowledge and experience gained in achieving the first aim.

The literature review revealed that continuous passive motion therapy (CPM) therapy was widely accepted for knee rehabilitation but not for the hand. Indeed, the published clinical studies into hand CPM were limited in number. The principal ones are listed in table 8.1.

Joint stiffness & limited range of movement	McLardy-Smith *et al* (1986) Ketchum *et al* (1979)
Reduction of oedema	Petronie and Calvanio (1989)
Flexor tendon repair	Cullen *et al* (1989) Bunker *et al* (1989) Gelberman *et al* (1991)
Burn injuries	Covey *et al* (1988)
General rehabilitation	Morris (1987)

Clinical studies into the role of hand CPM
table 8.1

The literature review also revealed that there was a surprisingly wide variety of hand CPM machines, though they could be grouped into three types, depending upon the type of motion they provided. A list is provided in table 8.2.

Arcuate motion devices	Ketchum *et al* (1979)	Not adopted
	Koerner *et al* (1985)	Adopted by the Sutter Corporation, USA
	Yates *et al* (1987)	Not adopted
	Kinetec 8080 machine	Adopted by the Kinetec Corp, France
	Greuloch *et al* (1992)	Adopted by Danniger Corp, USA
	Schenck (1986, 1988)	Not adopted
	Mobilimb H3	Adopted by Toronto Corp, Canada *(w/d)*
Linear reciprocating devices	Mobilimb H1	Adopted by Toronto Corp, Canada *(w/d)*
	Mobilimb H2	Adopted by Toronto Corp, Canada *(w/d)*
	A5000	Adopted by Pasbrig Co, Switzerland
Expandable and flexible palmar devices	Pschenichny & Kucherenko	Not known
	Takahashi and Mikiya	Not known
	Bentham *et al* (1987)	Not known

Hand CPM machines, classified in terms of the type of motion they provide
table 8.2

Thought was given to conducting the research with one of the commercially available machines listed above, but no criteria could be identified to decide which machine to use, because none had emerged as a front-runner. It was felt that it was important that the research be directed at investigating the *effects* of hand CPM, rather than the efficacy of using a *particular type* of machine. Accordingly, two special-purpose instrumented hand CPM machines were developed for clinical trials in Berlin and Dundee. The Berlin machine was used for assessing patients' treatment, firstly through measurements in the before-and-after changes in finger joint angles and secondly through measurements in the changes in force exerted by the machine to move stiffened finger joints, in order to gauge the reduction in finger joint stiffness. The Berlin trials revealed a persistent and troublesome problem associated with the attachment of the machine to a finger. To overcome this problem, a finger linkage had to be developed, though this was not initially identified as a requirement. The Dundee machine was used to specifically evaluate this linkage.

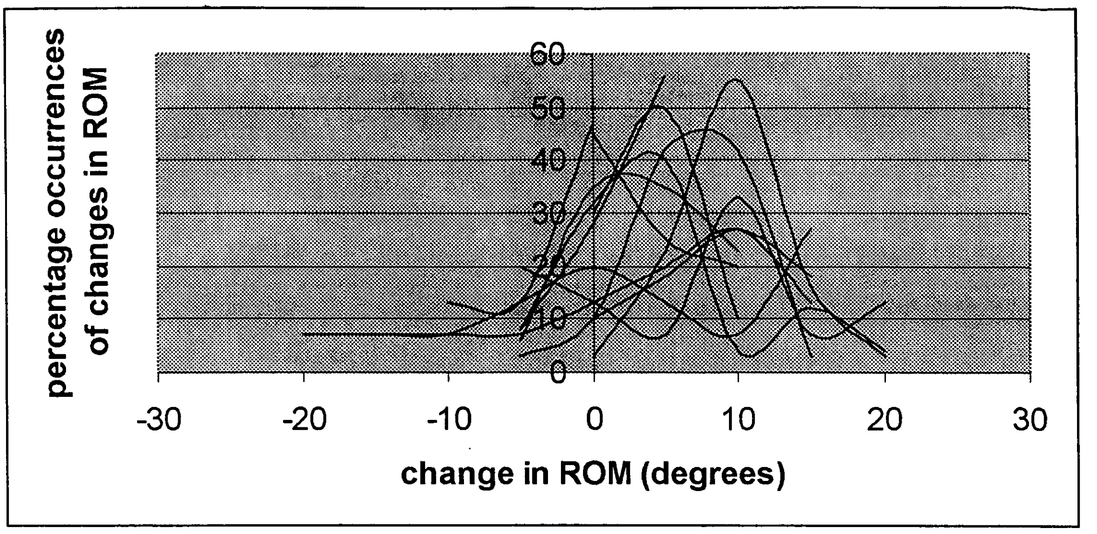
Finally, there was no established opinion about how long hand CPM should be applied and hence how long the clinical trials should last. Accordingly, a study was made of the recovery and return of strength after surgery for Dupuytren's contracture, without hand CPM. Dupuytren's contracture was chosen because this could be regarded as a general condition for hand dysfunction. Patients with this aetiology have swelling in the palm and fingers post-surgery. A sample of forty eight patients were operated upon and their recovery assessed using strength tests. It was found that recovery was gradual and approximately linear in the two – eight week period after surgery. Using the assumption that hand strength is related to functional recovery, it was found that recovery takes eight weeks. It could be assumed therefore that, if clinically permissible, CPM should be applied as soon as possible and continued for eight weeks after surgery.

8.1.2 Effect of CPM upon finger joint range of motion (ROM)

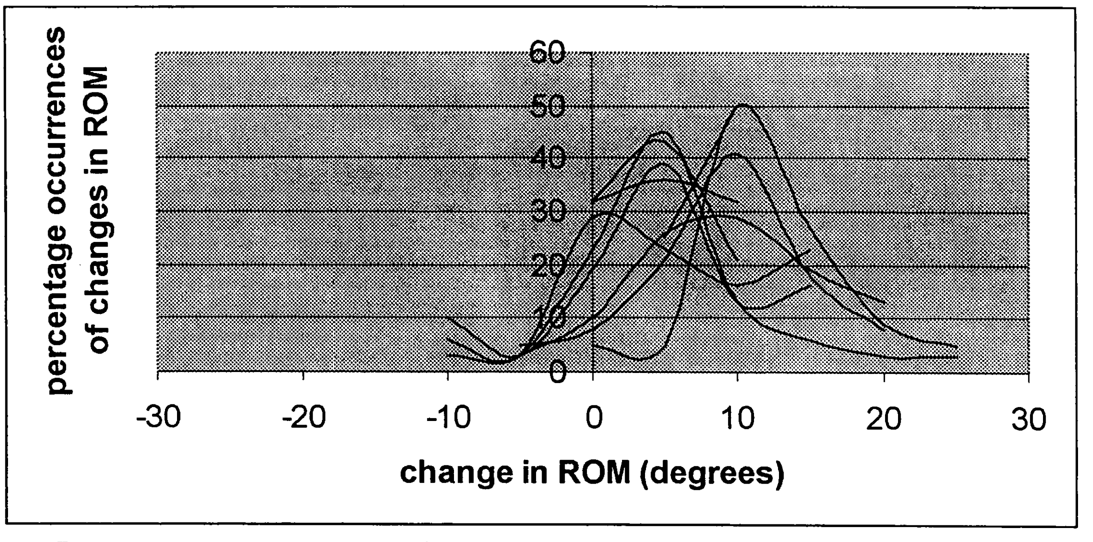
The changes in finger joint angles for the Berlin patients were processed to provide plots of the changes in maximum joint extension and flexion angles, and changes in joint range of movement. The latter was necessary to check that the treatment did not merely 'shift' the range of movement. The data was initially interpreted to determine the effect of CPM treatment on finger joint angles, measured pre- and post- each CPM treatment session, throughout the entire course of CPM treatment. The results are shown in appendix 5.2 and they were seen to be very similar to the 'zigzag' appearance of the results reported by Ketchum *et al* (1972, 1979).

The data were processed further by calculating the percentage occurrences of particular changes in finger joint angles, provided by each CPM treatment session. Results for individual patients are shown in appendix 5.3 and they are plotted collectively in figures 8.1 and 8.2. The results were generally very encouraging. Although some reductions in joint angles did occur (especially for the Sudeck patients #1;RB and #4;GZ) which are difficult to explain, the overall trend was encouraging with gains of 10 - 20 degrees being quite common.

It was clear however, that because of the zigzag nature of the cyclic gains & losses in finger joint ROM, when CPM was applied and then removed, the long term overall effects of ***all*** CPM treatment sessions on finger joint angles had also be considered. These results are shown in appendix 5.4 and summarised in table 8.3.



Percentage occurrences of changes in finger joint ROM – patients #3, 4, 5, 6, 7, 13
figure 8.1
phdconcs.xls



Percentage occurrences of changes in finger joint ROM – patients #14, 15, 16, 17
figure 8.2
phdconcs.xls

Patient	Finger Joint	ROM (before course of CPM treatment) *degrees*	ROM (after course of CPM treatment) *degrees*	Change in ROM *degrees*
#1 RB	MCP2	59	63	gain 4
	MCP3	63	69	gain 6
	MCP4	58	63	gain 5
	MCP5	60	66	gain 6
	PIP2	69	67	loss 2

continued/

Patient	Finger Joint	ROM (before course of CPM treatment) *degrees*	ROM (after course of CPM treatment) *degrees*	Change in ROM *degrees*
	PIP3	76	73	loss 3
	PIP4	78	78	no change
	PIP5	58	59	gain 1
	DIP2	27	29	gain 2
	DIP3	7	8	gain 1
	DIP4	14	16	gain 4
	DIP5	19	20	gain 1
	(MCP+PIP+DIP)2	154	158	gain 4
	(MCP+PIP+DIP)3	156	156	no change
	(MCP+PIP+DIP)4	150	157	gain 7
	(MCP+PIP+DIP)5	137	146	gain 9
# 3 MK	PIP2	26	28	gain 2
# 4 GZ	PIP2	34	39	gain 5
	PIP3	32	31	loss 1
	PIP4	22	20	loss 2
	PIP5	19	20	gain 1
# 5 CDB	PIP4	10	13	gain 3
# 6 AM	PIP3	33	37	gain 4
	PIP4	22	25	gain 3
# 7 CM	PIP2	41	43	gain 2
	PIP3	35	44	gain 9
	PIP4	26	27	gain 1
	PIP5	30	32	gain 2
# 13 Ma	PIP2	44	54	gain 10
	PIP4	27	30	gain 3
	PIP5	32	39	gain 7
# 14 Ha	MCP2	81	87	gain 6
	MCP3	82	88	gain 6
	PIP2	49	59	gain 10
	PIP3	61	69	gain 8
# 15 ML	PIP5	63	77	gain 14
# 16 Ka	MCP4	71	77	gain 6
	MCP5	66	76	gain 10
	PIP4	72	77	gain 5
	PIP5	65	70	gain 5
# 17 Jo	PIP4	31	36	gain 5
# 18 Wi	MCP2	80	80	no change
	MCP3	81	79	loss 2
	MCP4	73	72	loss 1
	PIP2	98	97	loss 1
	PIP3	95	95	no change
	PIP4	85	83	loss 2
	DIP2	58	56	loss 2
	DIP3	66	64	loss 2
	DIP4	46	47	gain 1

Summary of the long term overall effects of ***all*** *CPM treatment sessions on finger joint angles*
table 8.3

The patients with the best results were #13, #14, #15 and #16 (i.e. those with a variety of crush injuries, lacerations and fractures). Patients with poor results were #1 and #4 (both Sudeck), #3, #5, #6 and #18 (all with significant delays between surgery and CPM treatment), #7 (suicide attempt) and #17 (reason not known). However, the number of patients was small and it was not possible to correlate the long term outcome of CPM treatment with particular patient categories.

In conclusion, the principal benefit of applying hand CPM was an immediate gain in finger joint ROM, which almost invariably occurred and provided typical gains of 10 – 20 degrees. This beneficial effect was observed by both the patients and therapists and was a cause for enthusiastic acceptance of CPM treatment. However, these gains were generally lost when CPM was removed, so finger joint ROM had a zigzag pattern of gains and losses, associated with the application and removal of the machine.

Applying static orthoses might have reduced the losses in joint ROM, by keeping joints extended between CPM treatment sessions though this was not in fact attempted, so the possible benefits of applying static orthoses are not known.

It has to be stated that although patients liked the effects of CPM, they did comment that long treatment sessions were boring and interfered with their normal daily routines. For these reasons, each treatment session typically lasted one hour, though this duration was an arbitrary decision. It is not known whether prolonging CPM treatment would have altered the cyclic pattern of gains and losses in finger joint ROM and provided better results.

The duration of CPM treatment could have been extended by making the machine available for home use but this was impractical because clinical supervision was considered essential.

In the long term, all patients gained modest improvements in ROM, measured between the start and end of the entire course of treatment. However, the effects on the two patients with Sudeck contractures, the patient who had made the suicide attempt and the patient with an established Dupuytren's contracture were all minimal. It is possible that psychological factors may have effected the results for the first three patients. Finally, it is worth repeating that patients liked the effect of CPM and that the gains in joint range of motion were obvious to them.

8.1.3 Magnitude of forces applied during hand CPM

Each patient test typically comprised of five minutes of cyclic finger joint movement, followed by a two minutes pause at the limit of the machine's movement, to keep the joints in full flexion or extension as appropriate. Force data were recorded throughout the patient tests but their analyses were hampered by their size (35.5 megabytes) so they were interpreted on a macro level. Plots were provided of the maximum, mean and minimum force values, which occurred during each cyclic action between rest periods. It was found that data was made irregular by the following extraneous factors;

(i) Repositioning of the machine or finger thimble because of slippage of the velcro or elastoplast tapes
(ii) Active movement by the patient
(iii) 'Settling-in' at the start of CPM treatment
(iv) Passive tissue stretching in the rest periods between periods of cyclic movement
(v) Force-coupling between adjacent fingers

Disturbances in force data caused by the first two factors were random events, not associated with any changes in tissue response to the application of CPM. Hence, the data patterns were inspected and any which were found to be irregular and clearly caused by these two actors, were excluded from the analysis.

The magnitudes of the forces applied by the CPM machine were surprisingly high. Peak tensile forces (finger flexion) were in the range 10 - 15 Newtons and peak compressive force (finger extension) was 10 Newtons. Indeed, the limiting factor in applying forces of these magnitudes was the practical difficulty of keeping the machine physically attached to the patients' fingers.

The trends in the magnitudes of force exerted during CPM treatment are shown in table 8.4 below, which is a summary of the plots provided in table 7.15 (pages 224 – 236). Although trends were observed, there was some disappointment that the trends were neither dramatic nor consistent.

patient:	Maximum and minimum values	Standard deviation – force	Percentage of data above mean value	Overall increase in joint ROM
3 (actuator 1)	yes	Yes	yes	poor
4 (both actuators)	no	Yes	no	poor
5 (actuator 2)	yes (partially)	yes (partially)	yes (partially)	poor
6 (both actuators)	no	Yes	no	poor
7 (actuator 2)	yes	Yes	no	poor
8 (actuator 2)	yes	Yes	yes (partially)	no ROM result
9 (actuator 1)	yes	Yes	no	no ROM result
10 (actuator 2)	yes	Yes	yes	no ROM result
12 (both actuators)	no	No	no	no ROM result
13 (both actuators)	yes (partially)	yes	no	good
14	yes (partially)	yes (partially)	no	good

Summary table of the results of CPM treatment applied to the Berlin patients, assessed using maximum, minimum and mean force values, standard deviation and percentage of data above mean value
table 8.4

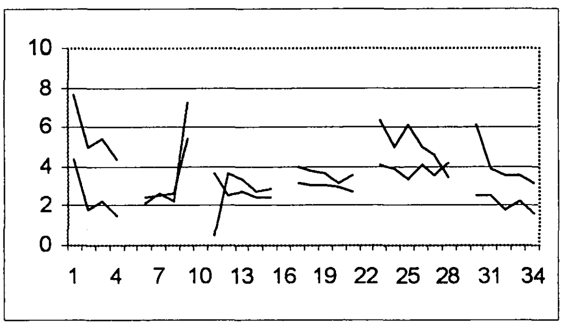
It was decided that the most likely reason the trends were not consistent was force-coupling between adjacent fingers, because the movement of one finger interfered with the force data recorded for its adjacent one. The therapists had ensured that when the machine was applied to a patient, the two actuators moved in phase with one another, so that the patient's adjacent fingers flexed and extended together. With this fitting procedure, the actuators did not do equal amounts of work and one actuator could do work on two fingers. It was impossible to interpret the force signal for one actuator (i.e. one finger) in isolation from the effects caused by the other.

These two factors, namely (i) force-coupling between adjacent fingers and (ii) the requirement to move fingers in phase with one another, probably caused some of the unexpected patterns in force magnitudes. There were occasions when the magnitudes of maximum applied force *increased*, even though it might be expected that increases in finger joint ROM would be associated with *decreases* in exerted CPM force. For example, the CPM forces applied to patient #6 *increased* on a number of tests, which can be seen in the see-saw changes in figure 7.15 (pages 227 and 228). However, on only 8 % of this patient's twenty-five tests was there a decrease in finger joint ROM (see appendix 5.3). The correlation between the patterns force data and the overall increase in joint ROM is described as *poor* in table 8.4 above.

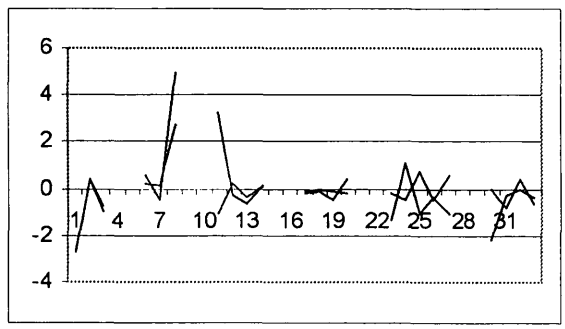
There were occasions when only one actuator was applied to a patient, namely patient #3 (third set of tests for actuator 1, page 224) and patient #10 (first four sets of tests for actuator 2, page 233). For both these patients, force-coupling could not occur and the trends in the reductions in maximum force magnitudes are clearly evident.

Two patients, #13 and #14 had *both* significant improvements in ROM *and* clear trends in the magnitudes of the maximum forces applied by both actuators of the machine. The suggestion that both actuators had worked together in increasing joint ROM was tested for these patients by plotting (i) the maximum values of applied tensile force for both actuators and (ii) the differences between successive maximum values of applied force, also for both actuators. The results are shown in figures 8.3(i) & (ii) for patient #13, and figures 8.4(i) & (ii) for patient #14. The force data has been extracted from appendix 5.5

Patient #13 – positive improvement in finger joint ROM

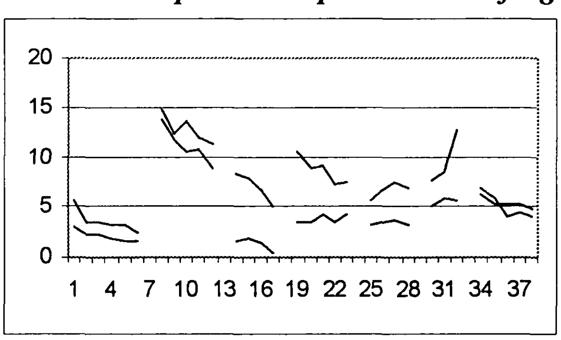


maximum values of applied tensile force - both actuators
figure 8.3(i)

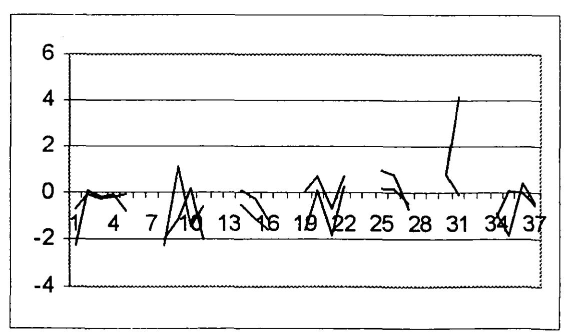


differences between successive maximum values of applied force – both actuators
figure 8.3(ii)

Patient #14 – positive improvement in finger joint ROM



maximum values of applied tensile force - both actuators
figure 8.4(i)

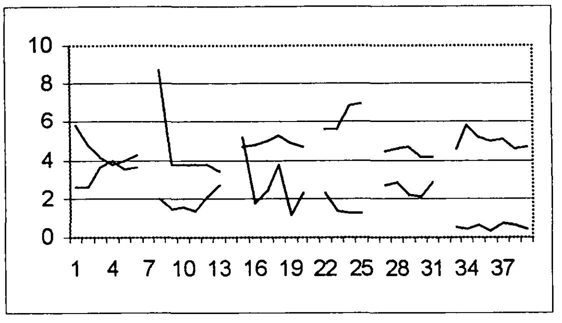


differences between successive maximum values of applied force – both actuators
figure 8.4(ii)

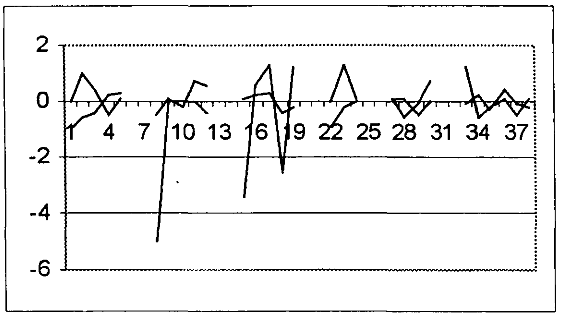
Clearly, the actuators behaved in a similar (though not exact) fashion for both patients. There was symmetry in the force actions applied by both actuators so the force-coupling between them was minimal.

The same could not be said for patients #4 and #6, which can be seen from figures 8.5 (i) & (ii) and 8.6 (i) and (ii). These plots lack the symmetry seen in figures 8.3 & 8.4. For both patients, the maximum value of applied force would sometimes decrease for one actuator, but simultaneously increase for the other.

Patient # 4 – Smith fracture followed by Sudeck contracture; minimal improvement in joint ROM

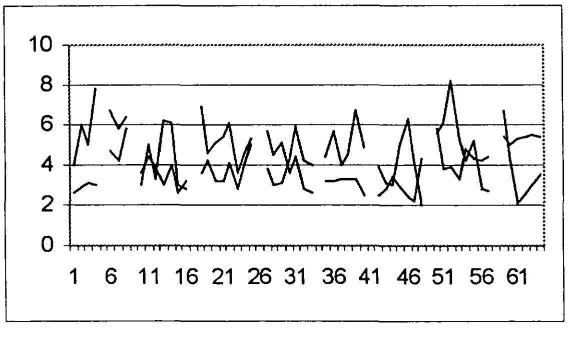


maximum values of applied tensile force - both actuators
figure 8.5(i)

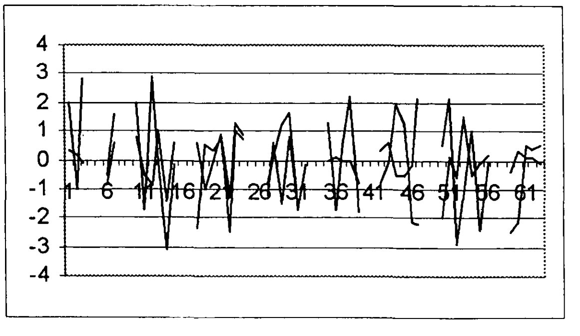


differences between successive maximum values of applied force – both actuators
figure 8.5(ii)

Patient #6 - poor ROM result probably caused by long delay between injury/surgery and application of CPM



maximum values of applied tensile force - both actuators
figure 8.6(i)



differences between successive maximum values of applied force – both actuators
figure 8.6(ii)

Finally, it was not surprising that the two actuators would apply both compressive force (to push finger joints into extension) and tensile force (to pull finger joints into flexion), during a single treatment session. The predominant compressive and tensile force requirements for all the patient tests are illustrated in table 8.5.

Patient	*Actuator 1*	*Actuator 2*
# 3	tension	compression
# 4	tension	tension & compression
# 5	no data	tension and compression
# 6	predominantly tension	predominantly tension
# 7	tension	tension
# 8	tension and compression	predominantly tension
# 9	tension and compression	predominantly compression
# 10	(ignored)	predominantly tension
# 12	tension and compression	predominantly tension
# 13	predominantly tension	tension
# 14	predominantly tension	predominantly tension

Compressive and tensile force requirements – patient tests
table 8.5

In conclusion, patients repeatedly asked the therapists to increase the force applied during CPM, because they liked the feeling of tissue stretching. Applied forces had high magnitudes and were often limited by the practical difficulties of attaching actuators to fingers.

Erratic plots of the magnitudes of the maximum CPM forces indicated the strong possibility that the force to move one finger affected the force required to move its adjacent one (i.e. force-coupling between adjacent fingers). The movement of one finger interfered with the force data recorded for the adjacent one.

Some patients had both significant long-term improvements in ROM and obvious trends in the magnitudes of the maximum forces applied by the actuators, during treatment sessions. For these patients, combined plots of the maximum forces exerted by both actuators showed symmetry and this indicated that they had worked together in increasing joint ROM.

In general, it was not possible to predict a match between the long term increases in joint ROM and changes in the magnitudes of force exerted during CPM therapy sessions.

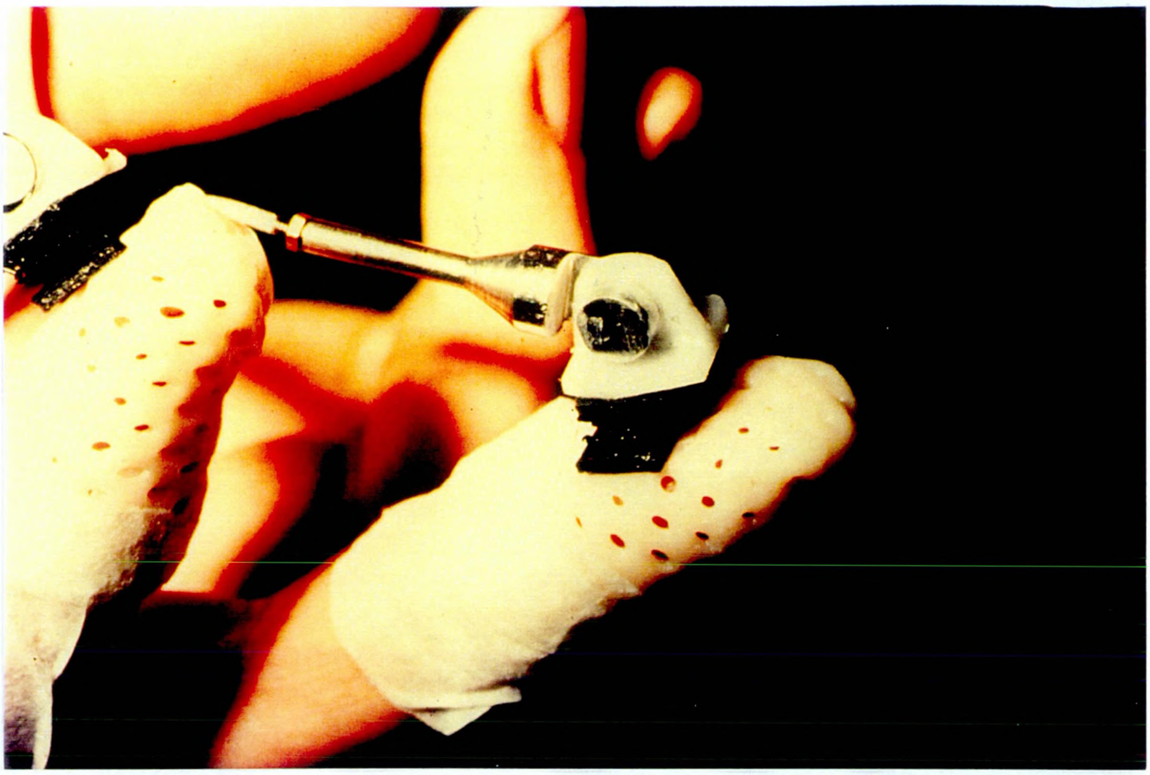
8.1.4 Finger linkage

Difficulties in attaching the CPM machine's actuator rod to patients' fingers were considerable and they impeded the research programme. The first method that was attempted, shown in figure 8.7, shows an actuator rod attached to a pivot, which is in turn attached to a thermoplastic thimble using velcro pads. The method proved to be unsuitable because the surgical tape wrapped around the proximal end of the thimble did not have sufficient adhesive strength to bind it to the finger. The second method, shown in figure 8.8, shows a Stack™ thermoplastic splint, modified to accept a pivot for the actuator rod, taped onto a finger. This method was also unsuitable because blood flow was often restricted (as shown in the figure) and because the splint prevented movement at the DIP joint. Figure 8.9 shows the same splint with a goniometer attached to the PIP joint. Whenever the Stack splint slipped off the finger, it would pull and destroy the goniometer.

The third method, shown in figure 8.10, involves the use of a low-temperature thermoplastic splint, specially designed and moulded for each individual patient. This splint could provide better attachment to the finger as well as a better arc of joint movement, but it still impeded movement of the DIP joint.

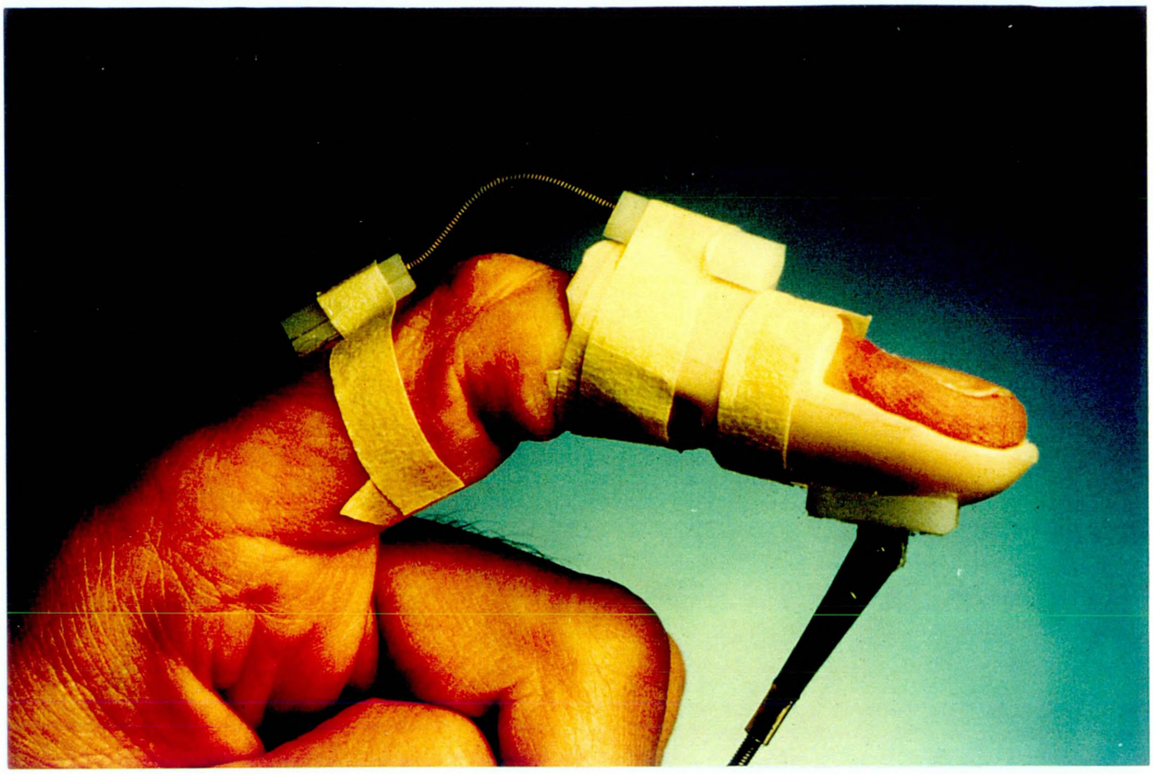
Because of these problems, it was found necessary to develop the linkage (previously illustrated in figures 5.26, 5.27 and 7.16 (pages 136, 137 and 237) which could mobilise finger joints in a selective manner. Unfortunately, it was developed at a late stage in the research programme so its evaluation had to limited to a series of clinical tests undertaken in Dundee. These tests were not performed to monitor and assess patients' courses of recovery *per se*, but to identify shortcomings in the behaviour of the linkage and ways of improving it.

The linkage was used with considerable success and it was shown to be the best method. It was shown that the linkage could apply forces over the entire finger, not just the distal phalanx. The tests were conducted on patients who had suffered Colles fractures, of whom there was regrettably a plentiful supply in winter months, when elderly people slipped on ice. It was shown that the linkage was effective in increasing joint ROM. For instance, there



Actuator rod attached to a pivot, which is in turn attached to a thermoplastic thimble using velcro pads.
figure 8.7

A Stack™ thermoplastic splint, modified to accept a pivot for the actuator rod, taped onto a finger
figure 8.8



A Stack™ thermoplastic splint, with a goniometer attached to the PIP joint
figure 8.9

A low-temperature thermoplastic splint, specially designed and moulded for each individual patient.
figure 8.10

was a clinical certainty that CPM had led to a functional improvement for patient EH, whose injury had resulted in MCP joint swelling and subsequent reduction in range of movement. A single test, conducted soon after her Plaster-of-Paris bandage was removed, resulted in a gain of twenty degrees in the MCP joint. Notwithstanding this rewarding result, one sour note has to be commented upon. This improved joint ROM had been achieved at the expense of fluid being 'pumped' into the adjacent MCP joints which both suffered a *reduction* of ten degrees in MCP joint range of motion. This experience reinforced the earlier finding (section 6.2, page 180) that the entire hand must be treated, not a single finger.

Unfortunately, time restrictions meant that the full facilities of the single actuator Dundee machine were not fully used, although this machine was made available for future clinical tests, after the completion of this research.

8.1.5 Adequacy of CPM for rehabilitation after flexor tendon repair

The second aim of the research was to investigate the development of a prototype CPM machine for the rehabilitation of flexor tendon repairs because the deformities that can occur after flexor tendon lacerations may be both severe and permanent. The Kleinert elastic band method for rehabilitation is well accepted but it depends upon good patient motivation. Patients are required to actively move their fingers, against the resistive tractive force applied by the elastic band, for a few minutes every half an hour during his/her woken hours, for six weeks after surgery. Whenever patients fail to follow this routine, because of poor motivation, lack of understanding, forgetfulness, or pain, the long-term functional results can be poor. CPM offers the possibility of providing powered continuous movement, which could overcome these four problems.

To be successful, a hand CPM machine for flexor tendon injuries must;

(i) be able to move all three finger joints, especially the DIP joint
(ii) be completely safe, so that it always moves finger joints in a controlled fashion between pre-determined limits
(iii) be used at a patient's home, so that the patient can have many hours of continuous passive motion

The first matter has already been addressed in the description and discussion of the linkage. The linkage could be suitable, in its non-instrumented version, although further clinical testing would be needed. The other two matters are discussed below.

8.1.5.1 Safety issues

The safety issue is problematic. The development of safe software was shown to be a particularly grey and sometimes worrying area. For this research programme, software for both the control of the machine and for data collection were operated under a Windows™ environment during the course of the tests in Dundee. It was observed that multi-tasking software could result in loss of control of the machine, which did on occasions move in an unpredictable way that might be dangerous. Problems were also encountered with the other machine (used in Berlin) which had its own dedicated microprocessor. A conclusion of the research programme was that considerable attention would have to be paid to the development of software that had safety-critical implications, i.e. those for which failure could result in 'absolute harm'. Hand CPM machines designed for use after flexor tendon repairs would fall into this category. The most important requirement is that the system must fail in a way that is safe, a condition that was difficult to guarantee in this research programme.

It is concluded that 'watch-dog' facilities are essential, which would consist of a secondary program operating in its own microprocessor, whose function is to continuously monitor the primary program. The watch-dog facilities would have overall hierarchical control of the system. In addition, mechanical end-of-travel stops would also be essential, as well as emergency stop buttons.

8.1.5.2 CPM use at home

There are stringent specifications for a CPM machine, which could be used by a patient at home. The machine would have to be simple to apply and use, comfortable, and it must have warning features to advise users of any malfunction. It would be a class 2 medical device defined in the context of the European Medical Device Directive, so a CE mark would be essential. Ideally, the machine would also be portable, have no electric mains supply and be body-mounted for personal mobility.

The only known machine in the World that currently approaches these requirements is the Danniger product (Greuloch *et al* 1992), though that machine is large and difficult to apply. Unfortunately, the two machines developed in this research programme did not meet these requirements. Nevertheless, a significant amount of work was accomplished at the end of the research, on the development of a another machine, which would be suitable. This is described in section 8.2.3.

8.2 Discussion

The clinical and technical experiences, gained during the research and clinical tests, are discussed below.

8.2.1 Clinical experience in the application of hand CPM

The clinical experience revealed that patients repeatedly reported they liked the application of CPM and the feeling of tissue being stretched. However, it is ironic that a number of patients complained that if the wrist joint were immobilised when CPM mobilised the finger joints, the wrist joint subsequently ached. This suggests that future hand CPM machines should not restrict wrist movement.

A further comment that was frequently made concerned the wish of some patients to readjust the range of movement of the machine, during a period of CPM treatment. This possibility was resisted during this research because any changes would disrupt a test. Nevertheless, CPM caused some dramatic changes in joint range of movement (ROM). For instance, patient RB (#1) had a maximum MCP2 joint flexion angle of 50 degrees before treatment, which was increased to 70 degrees after treatment. It could be reasoned that changes in the range of actuator movement could compensate for any loosening of joint tissue and provide even greater ROM. Furthermore, loosening of joint tissue would be accompanied by a reduction in actuator force to move the joint. This gives rise to the suggestion that a so-called 'intelligent' machine could be made, which could automatically adjust its range of movement automatically in response to changing force signal. The operating characteristics of an 'intelligent' machine would vary during the course of treatment, in order to optimise its functional performance. An 'intelligent' machine would require sensitive force transducers, which could be similar to the three component transducer designed in this project.

It has been shown that there are a number of factors that affect the force signals of a CPM machine, for instance force-coupling from one finger to another. The algorithms for controlling the range of movement of an 'intelligent' machine would not be simple to develop. It could not, for instance, be programmed to make an immediate response to a reduction in force signal. Instead, it is suggested that 'averaging routines' would be necessary and the machine's control would have to be rule-based.

8.2.2 Technical experience in the application of hand CPM

The technical experience gained during the research concerned the practical issues of machine reliability and efficiency.

8.2.2.1 Reliability

Although it could be reasoned that reliability problems could be prevented by good design practice, it must be stressed that the mechanical work which has to be done by hand CPM machines is considerable, especially when they have to repeatedly apply forces of the magnitudes recorded in this research. Regrettably, much of the available time set aside for this research was wasted because of machine unreliability. For instance, machine failure was caused by the ingress of hard dirt particles (worn from the rotating actuator spindle) into the ball races that caused seizure. Another location of wear was in the motor's gearbox, where deterioration in the first gear train and the bearings of the output shaft eventually caused machine failure.

The Berlin machine had a high usage, with a subsequent high mechanical wear rate of moving components. In the first trial year conducted in the occupational therapy department at the Oskar-Helene-Heim Hospital, the machine provided 250 hours of service in which time the actuator rods 'travelled' a distance of four kilometres and the motors rotated thirty million revolutions. In order to emphasise the required work capacity of CPM machines, the total distances which the actuators 'travelled' during the definitive Berlin patient tests is illustrated in table 8.6 below.

patient	*treatment duration*	*actuator 1 - metres travelled*	*actuator 2 - metres travelled*
#3	2 hours 8 minutes	9.6	6.3
#4	6 hours 46 minutes	10.3	12.8
#5	4 hours 41 minutes	17	7.3
#6	10 hours 56 minutes	25.4	23.3
#7	9 hours 54 minutes	34.2	35.6
#8	13 hours 25 minutes	80.7	74.6
#9	3 hours 47 minutes	26.5	17.8
#10	3 hours 40 minutes	18.8	1.9
#12	2 hours 52 minutes	15.2	11.6
#13	6 hours 12 minutes	40.9	35.7
#14	6 hours 30 minutes	53.6	60.5
total:	**70 hours**	**332 metres**	**288 metres**
	revs turned by motor at gearbox input:	1.47 million	1.66 million

Actuator distances 'travelled' during the Berlin patient tests
table 8.6

Discussions held with manufacturers of miniature d.c. motors revealed that their products could not in general meet these demands. It appears that for the immediate future, regular refurbishment programmes will be an irritating necessity for machines with miniature motors.

8.2.2.2 Machine efficiency

It would be desirable to have a machine that is battery driven so that it could be made portable. Efficiency tests on the second (Dundee) machine revealed that its motor drew 75 mA at a voltage of 5.62 volts; hence its power input is 0.422 watts. The machine could lift a mass of 0.5 kg through a distance of 50 mm in 18 seconds, so its rate of doing work was 0.0136 watts. Hence, its overall efficiency was only 3.2% ! Towards the end of the project period, new rechargeable lithium-ion batteries became available on the market, at an affordable cost. These batteries weigh 100 gms only and have an energy density of 1100 mAh. It is the emergence of these batteries, which offers the prospect of self-contained portable CPM machines in the future.

8.3 Recommendations for future work

It will be increasingly important in the future, to conduct formal trails to demonstrate both the clinical and cost effectiveness of hand CPM. The original emphasis of CPM was upon its *preventative* benefits – to *prevent* haematoma and oedema, *prevent* the formation of adhesions, *prevent* formation of scar tissue, *etc* – but it is extremely difficult to conduct a clinical trial whose measurable outcome is a demonstration that an adverse effect had been prevented. Histological examinations of collagen and articular tissue are clinically unnecessary and hence ethically unacceptable so it seems inevitable that clinical trials have to be restricted to measurable parameters such as increases in joint range of motion and changes in applied force. It is recommended that clinical trials should be conducted, using these two measurable parameters, to assess the effectiveness of hand CPM for particular clinical categories (Dupuytren's contractures, arthroplasties etc). Existing clinical trials are considered to be too wide-ranging and too broad.

Further research is needed to determine the reasons why improvements in joint range of motion (ROM), obtained in CPM treatment, were usually lost when the machine was removed. Are the gains transitory because oedema returns or because the improvements are merely caused by stretching of tissue which cannot be retained? If CPM were applied for a longer period, would joint range of motion permanently improve? It is recommended that consideration be given to the possibility of conducting animal studies to investigate these topics.

At the completion of the research programme, further work was initiated to develop a waist-mounted battery-driven machine, which would operate finger linkages constructed from plastic components, via bowden cables. It is envisaged that a twin-actuator machine would drive four linkages. The machine and linkage were at an advanced stage of development at the completion of this research and it is recommended that clinical trials should be conducted in the future, to assess their effectiveness, particularly for rehabilitation of flexor tendon injuries.

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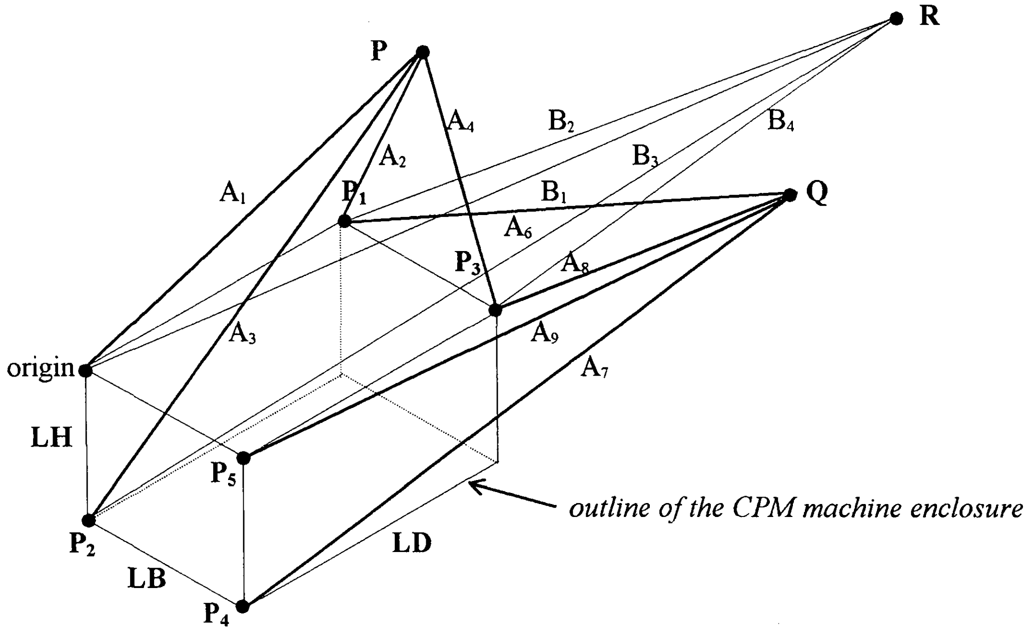
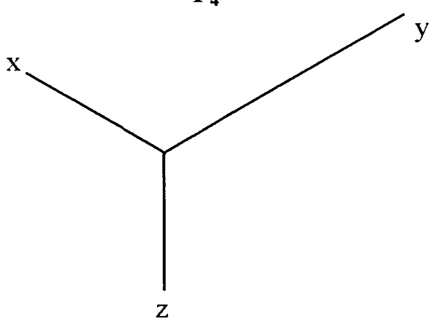
Procedures for determining the coordinates of a point using direct measurements from four nodes

The figure below illustrates the positions of vectors P & Q which are the radial and ulnar exit points, on the skin, of the wrist axis which passes through the carpus. R is a point on the dorsal side of the skin, above a finger's MCP or IP joint, as required. The coordinates of these three vectors must be found in an axis system, whose origin lies at the corner of the CPM machine's enclosure and whose axes lie along the edges of the enclosure.





axis system

$A_1 = \overline{0\,P}$
$A_2 = \overline{P_1\,P}$
$A_3 = \overline{P_2\,P}$
$A_4 = \overline{P_3\,P}$
$A_6 = \overline{P_1\,Q}$
$A_7 = \overline{P_4\,Q}$
$A_8 = \overline{P_3\,Q}$
$A_9 = \overline{P_5\,Q}$
$B_1 = \overline{0\,R}$
$B_2 = \overline{P_1\,R}$
$B_3 = \overline{P_2\,R}$
$B_4 = \overline{P_3\,R}$

The distances A_1, A_2, etc are measured from the corners of the enclosure to the required positions. Four nodes are used to determine the coordinates of each position.

Consider position P; from

$$A_1^2 = x^2 + y^2 + z^2$$

$$A_2^2 = x^2 + (y - LD)^2 + z^2 \qquad \textbf{(1)}$$

$$A_3^2 = x^2 + y^2 + (z - LH)^2 \qquad \textbf{(2)}$$

$$A_4^2 = (x + LB)^2 + (y - LD)^2 + z^2 \qquad \textbf{(3)}$$

Expanding equations (1), (2) and (3);

$$A_2^2 = x^2 + y^2 - 2y(LD) + (LD)^2 + z^2 \qquad \textbf{(4)}$$

$$A_3^2 = x^2 + y^2 + z^2 - 2z(LH) + (LH)^2 \qquad \textbf{(5)}$$

$$A_4^2 = x^2 + 2x(LB) + (LB)^2 + y^2 - 2y(LD) + (LD)^2 + z^2 \qquad \textbf{(6)}$$

Subtract (5) from (4);

$$A_2^2 - A_3^2 = -2y(LD) + (LD)^2 + 2z(LH) - (LH)^2$$

$$z = \frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)} \qquad \textbf{(7)}$$

Substitute (7) into (6);

$$A_4^2 = x^2 + 2x(LB) + (LB)^2 + y^2 - 2y(LD) + (LD)^2 + \left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2$$

Multiply both sides by $4(LH)^2$;

$$\begin{aligned}4A_4^2(LH)^2 = {} & 4x^2(LH)^2 + 8x(LB)(LH)^2 + 4(LB)^2(LH)^2 + 4y^2(LH)^2 - \\ & 8y(LD)(LH)^2 + 4(LH)^2(LD)^2 + \\ & [A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2]^2\end{aligned} \qquad \textbf{(8)}$$

Also;

$$A_1^2 = (x^2 + y^2 + z^2)$$

$$A_1^2 = x^2 + y^2 + \left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2$$

$$x = (PXS)\left[A_1^2 - y^2 - \left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2\right]^{0.5} \qquad \textbf{(9)}$$

The magnitude of x can be found from equation (9). The possibility that x might have a negative value is accounted for by testing for two solutions; where (PXS) = +1 and -1
Insert equation (8) and (9) into (7);

$$\begin{aligned}4A_4^2(LH)^2 = {} & 4(LH)^2\left[A_1^2 - y^2 - \left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2\right] + \\ & 8(LB)(PXS)(LH)^2\left[A_1^2 - y^2 - \left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2\right]^{0.5} + \\ & 4(LB)^2(LH)^2 + 4y^2(LH)^2 - 8y(LD)(LH)^2 + \\ & 4(LH)^2(LD)^2 + \left[A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2\right]^2\end{aligned} \qquad \textbf{(10)}$$

equation (10) can now be simplified.

Let; $\quad 4(LH)^2 = C1$

and;

$$\left[\frac{A_2^2 - A_3^2 + 2y(LD) - (LD)^2 + (LH)^2}{2(LH)}\right]^2 = C2$$

Then, from equation (10);

$$(C1)(A_4)^2 = (C1)\,[A_1^2 - y^2 - C2] + 2(LB)(C1)(PXS)[(A_1^2 - y^2 - C2)]^{0.5} + (LB)^2(C1) + y^2(C1) - 2y(LD)(C1) + (C1)(LD)^2 + (C2)(C1)$$

Divide through by (C1);

$$(A_4)^2 = [A_1^2 - y^2 - C2] + 2(LB)(PXS)[(A_1^2 - y^2 - C2)]^{0.5} + (LB)^2 + y^2 - 2y(LD) + (LD)^2 + (C2)$$

$$A_4^2 - A_1^2 + \cancel{y^2} + \cancel{(C2)} - (LB)^2 - \cancel{y^2} + 2y(LD) - (LD)^2 - \cancel{(C2)} = 2(LB)(PXS)[(A_1^2 - y^2 - C2)]^{0.5}$$

$$\frac{A_4^2 - A_1^2 - (LB)^2 - (LD)^2}{2(LB)} + \frac{y\,(LD)}{(LB)} = (PXS)[(A_1^2 - y^2 - C2)]^{0.5}$$

let;

$$\frac{A_4^2 - A_1^2 - (LB)^2 - (LD)^2}{2(LB)} = C3$$

so;

$$\left[C3 + \frac{y(LD)}{(LB)}\right]^2 = (PXS)^2\,[(A_1^2 - y^2 - C2)]$$

but $(PXS)^2$ must equal 1;

$$\left[C3 + \frac{y(LD)}{(LB)}\right]^2 = A_1^2 - y^2 - \left[\left[\frac{A_2^2 - A_3^2 - (LD)^2 + (LH)^2}{2(LH)}\right] + \frac{y(LD)}{2(LH)}\right]^2$$

let $C4 = \dfrac{LD}{LB}$ $\quad C5 = \dfrac{LD}{LH}$ $\quad C6 = \dfrac{A_2^2 - A_3^2 - (LD)^2 + (LH)^2}{2(LH)}$

then;

$$[(C3) + (C4)y]^2 = A_1^2 - y^2 - [C6 + (C5)y]^2$$

$$(C3)^2 + 2(C3)(C4)y + (C4)^2 y^2 = A_1^2 - y^2 - (C6)^2 - 2(C6)(C5)y - (C5)^2 y^2$$

$$y^2\,[(C4)^2 + 1 + (C5)^2] + y[2(C3)(C4) + 2(C6)(C5)] + [(C3)^2 - (A_1)^2 + (C6)^2] = 0$$

let

$$C7 = (C4)^2 + 1 + (C5)^2$$
$$C8 = 2(C3)(C4) + 2(C6)(C5)$$
$$C9 = (C3)^2 - (A_1)^2 + (C6)^2$$

then;

$$y^2\,(C4) + y\,(C8) + (C9) = 0$$

This is a quadratic in y. Its solution is used in equation (7) to determine the value for z and in equation (9) to determine the value for x. Similarly, the coordinates of points Q and R can be found using the vector distances A_6, A_7, A_8 & A_9 and B_1, B_2, B_3 & B_4

The equations developed above are used in the program ***CPM2.FOR*** (appendix 3.1) which was used to determine the coordinates of marks made on the radial and ulnar sides of the wrist joint and upon the dorsum sides of the metacarpal joints, with respect to the origin of the *CPM* machine. Marks made on the radial and ulnar sides of the wrist were identified as P and Q, and the distances A_1 - A_9 were measured and used in the program. Similarly, the coordinates of points on the dorsums of the metacarpal joints, R_1, R_2, R_3 and R_4 were computed. The program then calculated the rotations of the wrist axis with respect to *CPM* machine and the lengths of the metacarpals. Data was saved in data files ***CPMT*.DAT***, where the test number was inserted into the position of the asterix.

Program listing for *cpm2.for* to determine the coordinates of the wrist joint and the dorsal sides of the metacarpal joints with respect to the origin of the CPM machine

```
C     CPM2.FOR
      REAL A1,A2,A3,A4,A6,A7,A8,A9,B1,B2,B3,B4
      REAL LD,LB,LH
      REAL C1,C3,C4,C5,C6,C7,C8,C9,C12,C13,C14,C15
      REAL C16,C17,C19,C22,C23,C24,C25
      REAL COSA,COSAA,COSAAA,PXS,QXS,RXS,CNNFX,CNNFY,CNNFZ,PI
      REAL XP,YP,ZP,XQ,YQ,ZQ,XR,YR,ZR
      REAL XP1,YP1,ZP1,XP2,YP2,ZP2
      REAL XQ1,YQ1,ZQ1,XQ2,YQ2,ZQ2
      REAL XR1,YR1,ZR1,XR2,YR2,ZR2
      REAL XRI,YRI,ZRI,XRM,YRM,ZRM,XRR,YRR,ZRR,XRL,YRL,ZRL
      REAL Z,TIME
      CHARACTER*20 SNAME
      CHARACTER*20 CNAME
      INTEGER LIMB,DAY,MTH,YEAR,MCH,FINAT1,FINAT2,FINAT3,FINAT4
      INTEGER SKIP,NPTEST,NCTEST,SAVE
      INTEGER PAST(1,1)
C
C     Set variables, which might not be used, to zero ..
      XRI=0
      YRI=0
      ZRI=0
      XRM=0
      YRM=0
      ZRM=0
      XRR=0
      YRR=0
      ZRR=0
      XRL=0
      YRL=0
      ZRL=0
      FINAT1=0
      FINAT2=0
      FINAT3=0
      FINAT4=0
      SKIP=0
C
C     Determine how many tests have been undertaken previously ..
      OPEN (UNIT=5,FILE='TOTNO.TEST',STATUS ='OLD',ACCESS='SEQUENTIAL')
      K=99
      I=0
998   I=I+1
      READ (5,3,IOSTAT=K,ERR=999) PAST(1,1)
3     FORMAT (I4)
C
      GO TO 998
999   NPTEST=I-2
C
C     Unit 5 is kept open ..
C
C     Produce display menu ...
      DO 4 I=1,10
```

```
      WRITE (*,1)
1     FORMAT (3X,' ')
4     CONTINUE
      WRITE (*,5)
5     FORMAT(20X,'************************************')
      WRITE(*,1)
      WRITE (*,7)
7     FORMAT(20X,'   DETAILS OF THE APPLICATION OF')
      WRITE(*,9)
9     FORMAT(20X,'   THE CPM MACHINE TO A PATIENT')
      WRITE(*,1)
      WRITE (*,5)
C
      DO 12 I=1,3
      WRITE (*,1)
12    CONTINUE
      WRITE (*,14)
14    FORMAT (3X,'This program will accept details for twenty tests.')
      WRITE (*,16) NPTEST+1
16    FORMAT (26X,'This is test number',I4)
      IF (NPTEST.LT.19) THEN
      GO TO 22
      ELSE IF (NPTEST.EQ.19) THEN
      WRITE (*,1)
      WRITE (*,17)
17    FORMAT (21X,'EDIT THE PROGRAM AFTER THIS TEST!')
      ELSE
      WRITE (*,18)
18    FORMAT (30X,'PROGRAM ABORTED.')
      END IF
C
22    DO 23 I=1,3
      WRITE (*,1)
23    CONTINUE
C
      IF (NPTEST.EQ.20) GO TO 3000
      WRITE (*,25)
25    FORMAT (3X,'Press <ENTER> to continue')
      READ (*,1031) Z
      DO 30 I=1,40
      WRITE (*,1)
30    CONTINUE
C
      WRITE(*,50)
50    FORMAT (3X,'STEP 1:  ENTER THE DETAILS FOR THE PATIENT')
      WRITE (*,60)
60    FORMAT (3X,'________________________________________')
      DO 65 I=1,8
      WRITE (*,1)
65    CONTINUE
      WRITE (*,70)
70    FORMAT (3X,'Input the surname')
      READ (*,71) SNAME
71    FORMAT (A15)
      WRITE (*,1)
      WRITE (*,72)
72    FORMAT (3X,'Input the Christian name')
      READ (*,71) CNAME
```

```
      WRITE (*,1)
C
75    WRITE (*,76)
76    FORMAT (3X,'Enter "1" or "2" to select CPM application to')
      WRITE (*,80)
80    FORMAT (3X,'the left or right hand:')
      WRITE (*,82)
82    FORMAT (10X,'1   left hand')
      WRITE (*,84)
84    FORMAT (10X,'2   right hand')
      READ (*,163) LIMB
      IF (LIMB.GT.2) GO TO 75
      WRITE (*,25)
      READ (*,1031) Z
      DO 90 I=1,15
      WRITE (*,1)
90    CONTINUE
C
      WRITE(*,150)
150   FORMAT (3X,'STEP 2:  ENTER THE DETAILS OF THE TEST')
      WRITE (*,160)
160   FORMAT (3X,'_______________________________________')
      DO 161 I=1,8
      WRITE (*,1)
161   CONTINUE
      WRITE (*,162)
162   FORMAT (3X,'Input the day of the month (1-31)')
      READ (*,163) DAY
163   FORMAT (I4)
      WRITE (*,164)
164   FORMAT (3X,'Input the month of the year (1-12)')
      READ (*,163) MTH
      WRITE (*,166)
166   FORMAT (3X,'Input the last two digits of the year (eg "91")')
      READ (*,163) YEAR
      WRITE (*,168)
168   FORMAT (3X,'Input the start time of the test (eg "14.30")')
      READ (*,1031) TIME
178   WRITE (*,180)
180   FORMAT (3X,'Enter "1" or "2" to select the type of CPM machine')
      WRITE (*,181)
181   FORMAT (10X,'1   machine for two fingers')
      WRITE (*,182)
182   FORMAT (10X,'2   balsa wood machine!')
      READ (*,163) MCH
      IF (MCH.GT.2) GO TO 178
      IF (MCH.EQ.2) GO TO 230
C
C     Enter dimensions of two finger actuator. If the machine is on its broad bottom, then
C     LD=15.8, LB=7.9 and LH=5.0; alternatively, if it is on its narrow edge, LD=15.8, LB=5.0 C
      and LH=7.9 ..
C
      LD=15.8
      LB=5.0
      LH=7.9
C     State which actuator rod is applied to which finger ..
      WRITE (*,189)
189   FORMAT (3X,'Select which finger is moved by actuator 1')
```

```
      WRITE (*,190)
190   FORMAT (10X,' 1  Index Finger')
      WRITE (*,191)
191   FORMAT (10X,' 2  Middle Finger')
      WRITE (*,192)
192   FORMAT (10X,' 3  Ring Finger')
      WRITE (*,193)
193   FORMAT (10X,' 4  Little Finger')
      READ (*,195) FINAT1
195   FORMAT (I2)

C
      WRITE (*,210)
210   FORMAT (3X,'Select which finger is moved by actuator 2')
      WRITE (*,211)
211   FORMAT (10X,' 1  Index Finger')
      WRITE (*,212)
212   FORMAT (10X,' 2  Middle Finger')
      WRITE (*,213)
213   FORMAT (10X,' 3  Ring Finger')
      WRITE (*,214)
214   FORMAT (10X,' 4  Little Finger')
      READ (*,195) FINAT2
      GO TO 250
C
C     Enter dimensions of balsa wood model ..
230   LD=17
      LB=10
      LH=12
C
      WRITE (*,240)
240   FORMAT (3X,'Select which finger is moved by the actuator')
      WRITE (*,241)
241   FORMAT (10X,' 1  Index Finger')
      WRITE (*,242)
242   FORMAT (10X,' 2  Middle Finger')
      WRITE (*,243)
243   FORMAT (10X,' 3  Ring Finger')
      WRITE (*,244)
244   FORMAT (10X,' 4  Little Finger')
      READ (*,195) FINAT3
C
250   WRITE (*,25)
      READ (*,1031) Z
      DO 251 I=1,15
      WRITE (*,1)
251   CONTINUE
C
      WRITE (*,1010)
1010  FORMAT (3X,'STEP 3: DETERMINE THE POSITION OF THE WRIST WITH')
      WRITE (*,1015)
1015  FORMAT (3X,'RESPECT TO THE CONTINUOUS PASSIVE MOTION MACHINE')
      WRITE (*,1020)
1020  FORMAT (3X,'__________________________________________________')
      DO 1024 I=1,5
      WRITE (*,1)
1024  CONTINUE
C
```

```
      WRITE (*,1025)
1025  FORMAT (3X,'The following dimensions MUST be entered in')
      WRITE (*,1026)
1026 FORMAT (10X,'centimetres and MUST have a decimal point')
      WRITE (*,1)
      WRITE (*,1)
C
      WRITE (*,1030)
1030  FORMAT (3X,'Input A1 (A1 for balsa wood model is 29.0)')
      READ (*,1031) A1
C
      WRITE (*,1032)
1032  FORMAT (3X,'Input A2 (A2 for balsa wood model is 20.5)')
      READ (*,1031) A2
C
      WRITE (*,1034)
1034  FORMAT (3X,'Input A3 (A3 for balsa wood model is 22.1)')
      READ (*,1031) A3
C
      WRITE (*,1036)
1036  FORMAT (3X,'Input A4 (A4 for balsa wood model is 23.7)')
      READ (*,1031) A4
C
      WRITE (*,1038)
1038  FORMAT (3X,'Input A6 (A6 for balsa wood model is 19.5)')
      READ (*,1031) A6
C
      WRITE (*,1040)
1040  FORMAT (3X,'Input A7 (A7 for balsa wood model is 21.9)')
      READ (*,1031) A7
C
      WRITE (*,1042)
1042  FORMAT (3X,'Input A8 (A8 for balsa wood model is 17.1)')
      READ (*,1031) A8
C
      WRITE (*,1044)
1044  FORMAT (3X,'Input A9 (A9 for balsa wood model is 27.1)')
      READ (*,1031) A9
C
1031  FORMAT (F10.5)
C
      PI=3.1415927
      CT=0
      CTT=0
C
C     Determine the coordinates of the wrist axis adjacent to the CPM's origin
C
C     Account for the possibility that x might be negative
C     by setting PXS to 1 or -1 ..
      COSA=((A2**2)+(LB**2)-(A4**2))/(2*A2*LB)
      IF (A4.LT.LB) PXS=-1.0
      IF (A4.GT.LB.AND.COSA.LT.0) PXS=1.0
      IF (A4.GT.LB.AND.COSA.GT.0) PXS=-1.0
C
      C1=4*(LH**2)
      C3=((A4**2)-(A1**2)-(LB**2)-(LD**2))/(2*LB)
      C4=LD/LB
      C5=LD/LH
```

```
      C6=((A2**2)-(A3**2)-(LD**2)+(LH**2))/(2*LH)
      C7=(C4**2)+1+(C5**2)
      C8=(2*C3*C4)+(2*C5*C6)
      C9=(C3**2)-(A1**2)+(C6**2)
C
      YP1=(-C8+SQRT((C8**2)-(4*C7*C9)))/(2*C7)
      ZP1=((A2**2)-(A3**2)+(2*YP1*LD)-(LD**2)+(LH**2))/(2*LH)
      XP1=PXS*SQRT((A1**2)-(YP1**2)-(ZP1**2))
C
      YP2=(-C8-SQRT((C8**2)-(4*C7*C9)))/(2*C7)
      ZP2=((A2**2)-(A3**2)+(2*YP2*LD)-(LD**2)+(LH**2))/(2*LH)
      XP2=PXS*SQRT((A1**2)-(YP2**2)-(ZP2**2))
C
      WRITE(*,1)
      WRITE(*,1050)
1050  FORMAT (3X,'The possible coordinates for the wrist joint')
      WRITE(*,1052)
1052  FORMAT (3X,'adjacent to the origin of the CPM machine are;')
      WRITE(*,1055) XP1,YP1,ZP1
1055  FORMAT(10X,'XP = ',F8.4,8X,'YP = ',8X,F8.4,8X,'ZP = ',F8.4)
      WRITE(*,1057) XP2,YP2,ZP2
1057  FORMAT(5X,'and  XP = ',F8.4,8X,'YP = ',8X,F8.4,8X,'ZP = ',F8.4)
      WRITE(*,1)
C
C     Find the most likely coordinates by checking that for either solution, the values of y and z
C     are both positive and x has a sensible value ..
      IF (YP1.LT.LD.OR.ZP1.LT.0.OR.XP1.GT.10.OR.XP1.LT.-15) GO TO 1100
C     XP1,YP1,ZP1 are likely solutions ....
      XP=XP1
      YP=YP1
      ZP=ZP1
      CT=1
1100  IF (YP2.LT.LD.OR.ZP2.LT.0.OR.XP2.GT.10.OR.XP2.LT.-15) GO TO 1200
C
C     XP2,YP2,ZP2 are likely solutions ....
      XP=XP2
      YP=YP2
      ZP=ZP2
      CT=CT+1
1200  CONTINUE
C
      IF (CT.EQ.0) GO TO 1300
      IF (CT.EQ.2) GO TO 1267
C
      WRITE(*,1260)
1260  FORMAT (3X,'The likely coordinates for the wrist joint adjacent')
      WRITE(*,1262)
1262  FORMAT (3X,'  to the origin of the CPM machine are;')
      WRITE(*,1265) XP,YP,ZP
1265  FORMAT(10X,'XP = ',F8.4,8X,'YP = ',8X,F8.4,8X,'ZP = ',F8.4)
      WRITE (*,25)
      READ (*,1031) Z
C
      IF(CT.EQ.1) GO TO 1320
1267  WRITE(*,1270)
1270  FORMAT(3X,'WARNING:- BOTH SETS OF COORDINATES are possible')
      GO TO 1320
C     Neither set of coordinate values seems satisfactory ..
```

```
1300  WRITE (*,1310)
1310  FORMAT(3X,'Neither set of values seems satisfactory ..')
      GO TO 3000
C
C     It is now necessary to find the coordinates on the other side
C     of the wrist ..
C
1320  COSAA=((A6**2)+(LB**2)-(A8**2))/(2*A6*LB)
      IF (A8.LT.LB) QXS=-1.0
      IF (A8.GT.LB.AND.COSAA.LT.0) QXS=1.0
      IF (A8.GT.LB.AND.COSAA.GT.0) QXS=-1.0
C
      C12=((A8**2)-(A7**2)-(LD**2)+(LH**2))/(2*LH)
      C13=(A6**2)-(LD**2)
      C14=((A9**2)-C13-(LB**2))/(2*LB)
      C15=1+(C4**2)+(C5**2)
      C16=(2*C12*C5)-(2*C4*C14)-(2*LD)
      C17=(C14**2)-C13+(C12**2)
C
      YQ1=(-C16+SQRT((C16**2)-(4*C17*C15)))/(2*C15)
      ZQ1=((A8**2)-(A7**2)+(2*YQ1*LD)-(LD**2)+(LH**2))/(2*LH)
      XQ1=QXS*SQRT((A6**2)-((YQ1-LD)**2)-(ZQ1**2))
C
      YQ2=(-C16-SQRT((C16**2)-(4*C17*C15)))/(2*C15)
      ZQ2=((A8**2)-(A7**2)+(2*YQ2*LD)-(LD**2)+(LH**2))/(2*LH)
      XQ2=QXS*SQRT((A6**2)-((YQ2-LD)**2)-(ZQ2**2))
C
      WRITE(*,1)
      WRITE(*,1350)
1350  FORMAT (3X,'The possible coordinates for the wrist joint')
      WRITE(*,1352)
1352  FORMAT (3X,'opposite the origin of the CPM machine are;')
      WRITE(*,1355) XQ1,YQ1,ZQ1
1355  FORMAT(10X,'XQ = ',F8.4,8X,'YQ = ',8X,F8.4,8X,'ZQ = ',F8.4)
      WRITE(*,1357) XQ2,YQ2,ZQ2
1357  FORMAT(5X,'and  XQ = ',F8.4,8X,'YQ = ',8X,F8.4,8X,'ZQ = ',F8.4)
      WRITE (*,1)
C
C     Find the most likely coordinates by checking that for either solution, the values of y and z
C     are both positive and x has a sensible value. The value of ZQ is likely to be ZP+/- 5 cms
      IF (YQ1.LT.LD.OR.ZQ1.LT.0.OR.XQ1.GT.10.OR.XQ1.LT.-15) GO TO 1400
      IF (ZQ1.GT.(ZP+5).OR.ZQ1.LT.(ZP-5)) GO TO 1400
C     XQ1,YQ1,ZQ1 are likely solutions ....
      XQ=XQ1
      YQ=YQ1
      ZQ=ZQ1
      CTT=1
1400  IF (YQ2.LT.LD.OR.ZQ2.LT.0.OR.XQ2.GT.10.OR.XQ2.LT.-15) GO TO 1500
      IF (ZQ2.GT.(ZP+5).OR.ZQ2.LT.(ZP-5)) GO TO 1500
C
C     XQ2,YQ2,ZQ2 are likely solutions ....
      XQ=XQ2
      YQ=YQ2
      ZQ=ZQ2
      CTT=CTT+1
1500  CONTINUE
      IF (CTT.EQ.0) GO TO 1600
      IF (CTT.EQ.2) GO TO 1567
```

```
      WRITE(*,1560)
1560  FORMAT (3X,'The likely coordinates for the wrist joint opposite')
      WRITE(*,1562)
1562  FORMAT (3X,'  the origin of the CPM machine are;')
      WRITE(*,1565) XQ,YQ,ZQ
1565  FORMAT(10X,'XQ = ',F8.4,8X,'YQ = ',8X,F8.4,8X,'ZQ = ',F8.4)
      WRITE (*,25)
      READ (*,1031) Z
C
      IF(CTT.EQ.1) GO TO 1700
1567  WRITE(*,1570)
1570  FORMAT(3X,'  WARNING:- BOTH SETS OF COORDINATES are possible')
      GO TO 1700
C     Neither set of coordinate values seems satisfactory ..
1600  WRITE (*,1610)
1610  FORMAT(3X,'Neither set of values seems satisfactory ..')
      GO TO 3000
C
1700  CONTINUE
C
C     Now determine the positions of the metacarpals ..
C
1770  DO 1775 I=1,15
      WRITE (*,1)
1775  CONTINUE
      WRITE (*,1778)
1778  FORMAT (3X,'STEP 4: DETERMINE THE POSITION OF THE DORSUM OF')
      WRITE (*,1780)
1780  FORMAT (3X,'        THE METACARPAL JOINT WITH RESPECT TO THE')
      WRITE (*,1782)
1782  FORMAT (3X,'        CONTINUOUS PASSIVE MOTION MACHINE')
      WRITE (*,1784)
1784  FORMAT (3X,'____________________________________________')
C
C     Move from the index to the little finger
      DO 2400 J=1,4
C
      DO 1788 I=1,3
      WRITE (*,1)
1788  CONTINUE
      IF (J.EQ.1) THEN
      WRITE (*,1792)
1792  FORMAT (3X,'Enter details for the index finger')
      DO 1794 I=1,3
      WRITE (*,1)
1794  CONTINUE
      ELSE IF (J.EQ.2) THEN
      WRITE (*,1800)
1800  FORMAT (3X,'Enter details for the middle finger')
      DO 1802 I=1,8
      WRITE (*,1)
1802  CONTINUE
      ELSE IF (J.EQ.3) THEN
      WRITE (*,1805)
1805  FORMAT (3X,'Enter details for the ring finger')
      DO 1807 I=1,8
      WRITE (*,1)
1807  CONTINUE
```

```
      ELSE IF (J.EQ.4) THEN
      WRITE (*,1810)
1810  FORMAT (3X,'Enter details for the little finger')
      DO 1812 I=1,8
      WRITE (*,1)
1812  CONTINUE
      END IF
      DO 1813 I=1,6
      WRITE (*,1)
1813  CONTINUE
C
1814  WRITE (*,1815)
1815  FORMAT (3X,'The following dimensions must be entered in')
      WRITE (*,1818)
1818  FORMAT (10X,'centimetres and must have a decimal point')
      WRITE (*,1)
      WRITE (*,1)
      WRITE (*,1820)
1820  FORMAT (3X,'Press <1> if you wish to go to the next finger')
      WRITE (*,1825)
1825  FORMAT (5X,'without entering details for this finger')
      WRITE (*,1830)
1830  FORMAT (5X,'Enter details for this finger by entering <2>')
      READ (*,1835)SKIP
1835  FORMAT (I1)
C
      IF (SKIP.EQ.1) GO TO 2399
      IF (SKIP.EQ.2) GO TO 1845
      IF (SKIP.GT.2) GO TO 1814
      WRITE (*,1)
      WRITE (*,1)
C
1845  WRITE (*,1848)
1848  FORMAT (3X,'Input B1 (B1 for balsa wood model is 45.4)')
      READ (*,2039) B1
C
      WRITE (*,1852)
1852  FORMAT (3X,'Input B2 (B2 for balsa wood model is 33.1)')
      READ (*,2039) B2
C
      WRITE (*,1858)
1858  FORMAT (3X,'Input B3 (B3 for balsa wood model is 39.5)')
      READ (*,2039) B3
C
      WRITE (*,1866)
1866  FORMAT (3X,'Input B4 (B4 for balsa wood model is 33.2)')
      READ (*,2039) B4
C
2039  FORMAT (F10.5)
C
C     Determine the coordinates of the dorsum of the metacarpal with respect to the CPM's origin
C     Account for the possibility that x might be negative by setting RXS to 1 or -1 ..
      COSAAA=((B2**2)+(LB**2)-(B4**2))/(2*B2*LB)
      IF (B4.LT.LB) RXS=-1.0
      IF (B4.GT.LB.AND.COSAAA.LT.0) RXS=1.0
      IF (B4.GT.LB.AND.COSAAA.GT.0) RXS=-1.0
C
      CTTT=0
```

```
      C19=((B4**2)-(B1**2)-(LB**2)-(LD**2))/(2*LB)
      C22=((B2**2)-(B3**2)-(LD**2)+(LH**2))/(2*LH)
      C23=(C4**2)+1+(C5**2)
      C24=(2*C19*C4)+(2*C5*C22)
      C25=(C19**2)-(B1**2)+(C22**2)
C
      YR1=(-C24+SQRT((C24**2)-(4*C23*C25)))/(2*C23)
      ZR1=((B2**2)-(B3**2)+(2*YR1*LD)-(LD**2)+(LH**2))/(2*LH)
      XR1=RXS*SQRT((B1**2)-(YR1**2)-(ZR1**2))
C
      YR2=(-C24-SQRT((C24**2)-(4*C23*C25)))/(2*C23)
      ZR2=((B2**2)-(B3**2)+(2*YR2*LD)-(LD**2)+(LH**2))/(2*LH)
      XR2=RXS*SQRT((B1**2)-(YR2**2)-(ZR2**2))
C
      WRITE(*,1)
      WRITE(*,2050)
2050  FORMAT (3X,'The possible coordinates for the metacarpal are;')
      WRITE(*,2055) XR1,YR1,ZR1
2055  FORMAT(10X,'XR = ',F8.4,8X,'YR = ',8X,F8.4,8X,'ZR = ',F8.4)
      WRITE(*,2057) XR2,YR2,ZR2
2057  FORMAT(5X,'and  XR = ',F8.4,8X,'YR = ',8X,F8.4,8X,'ZR = ',F8.4)
      WRITE(*,1)
C
C     Find the most likely coordinates by checking that for either solution, the values of y and z
C     are both positive and x has a sensible value..
      IF (YR1.LT.LD.OR.ZR1.LT.0.OR.XR1.GT.10.OR.XR1.LT.-15) GO TO 2100
C     XR1,YR1,ZR1 are likely solutions ....
      XR=XR1
      YR=YR1
      ZR=ZR1
      CTTT=1
2100  IF (YR2.LT.LD.OR.ZR2.LT.0.OR.XR2.GT.10.OR.XR2.LT.-15) GO TO 2200
C
C     XR2,YR2,ZR2 are likely solutions ....
      XR=XR2
      YR=YR2
      ZR=ZR2
      CTTT=CTTT+1
2200  CONTINUE
C
      IF (CTTT.EQ.0) GO TO 2300
      IF (CTTT.EQ.2) GO TO 2267
C
      WRITE(*,2260)
2260  FORMAT (3X,'The likely coordinates for the dorsal side of ')
      WRITE(*,2262)
2262  FORMAT (3X,'  the metacarpal joint are;')
      WRITE(*,2265) XR,YR,ZR
2265  FORMAT(10X,'XR = ',F8.4,8X,'YR = ',8X,F8.4,8X,'ZR = ',F8.4)
C
      WRITE (*,25)
      READ (*,1031) Z
C
      IF(CTTT.EQ.1) GO TO 2320
2267  WRITE(*,2270)
2270  FORMAT(3X,'WARNING:- BOTH SETS OF COORDINATES are possible')
      GO TO 3000
C     Neither set of coordinate values seems satisfactory ..
```

```
2300  WRITE (*,2310)
2310  FORMAT(3X,'Neither set of values seems satisfactory ..')
      GO TO 3000
2320  CONTINUE
C
      IF (J.EQ.1) THEN
        XRI=XR
        YRI=YR
        ZRI=ZR
      ELSE IF (J.EQ.2) THEN
        XRM=XR
        YRM=YR
        ZRM=ZR
      ELSE IF (J.EQ.3) THEN
        XRR=XR
        YRR=YR
        ZRR=ZR
      ELSE IF (J.EQ.4) THEN
        XRL=XR
        YRL=YR
        ZRL=ZR
      END IF
      WRITE (*,1)
      WRITE (*,1)
C
2399  SKIP=0
2400  CONTINUE
C
C
C     Calculate the rotation angles of the wrist joint with respect to the CPM's axis system. First C
      determine the distance across the wrist joint ..
      AXIS= SQRT(((XP-XQ)**2)+((YP-YQ)**2)+((ZP-ZQ)**2))
C
C     DETERMINE THE ROTATIONS OF THE METACARPAL W.R.T. THE CPM AXIS
C     SYSTEM
C     First, determine the length of the metacarpal in order to find its X-rotation. Initially assume C
      that the base of the metacarpal is at the midpoint of the wrist axis;
      CNNFX=(XP+XQ)/2
      CNNFY=(YP+YQ)/2
      CNNFZ=(ZP+ZQ)/2
C
C     Assume the position of the origin of the MCP joint w.r.t. the dorsum position of the MCP
C     joint;
      ZMCP=5.5
C
      PHIX=ATAN(((ZR-ZMCP)-CNNFZ)/(YR-CNNFY))
      PHIY=ATAN((ZQ-ZP)/(XP-XQ))
      PHIZ=ATAN((YP-YQ)/(XP-XQ))
C
      PHIX=PHIX*180/PI
      PHIY=PHIY*180/PI
      PHIZ=PHIZ*180/PI
C
      WRITE (*,1)
      WRITE (*,1740)
1740  FORMAT(3X,'The rotations of the wrist axis with respect to the')
      WRITE (*,1743)
1743  FORMAT(3X,'CPMs frame of reference are;')
```

```
      WRITE (*,1750) PHIX,PHIY,PHIZ,AXIS
1750  FORMAT(3X,'PHIX = ',F7.2,'   PHIY = ',F7.2,'   PHIZ = ',F7.2,'
     C WRIST WIDTH = ',F5.2)
      WRITE (*,25)
      READ (*,1031) Z
C
C     Decide whether these test results should be saved or not ..
C
      DO 2420 I=1,25
      WRITE (*,1)
2420  CONTINUE
      WRITE (*,2430)
2430  FORMAT (3X,'Enter <1> if this data should be saved or')
      WRITE (*,2435)
2435  FORMAT (3X,'   or <2> if the data should be abandoned')
      READ (*,2440) SAVE
2440  FORMAT (I4)
      IF (SAVE.GE.2) GO TO 3000
C
C     Output values to data file "CPMT*.DAT"
      IF (NPTEST.EQ.0) THEN
      OPEN (UNIT=6,FILE='CPMT1.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.1) THEN
      OPEN (UNIT=6,FILE='CPMT2.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.2) THEN
      OPEN (UNIT=6,FILE='CPMT3.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.3) THEN
      OPEN (UNIT=6,FILE='CPMT4.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.4) THEN
      OPEN (UNIT=6,FILE='CPMT5.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.5) THEN
      OPEN (UNIT=6,FILE='CPMT6.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.6) THEN
      OPEN (UNIT=6,FILE='CPMT7.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.7) THEN
      OPEN (UNIT=6,FILE='CPMT8.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.8) THEN
      OPEN (UNIT=6,FILE='CPMT9.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.9) THEN
      OPEN (UNIT=6,FILE='CPMT10.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.10) THEN
      OPEN (UNIT=6,FILE='CPMT11.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.11) THEN
      OPEN (UNIT=6,FILE='CPMT12.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.12) THEN
      OPEN (UNIT=6,FILE='CPMT13.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.13) THEN
      OPEN (UNIT=6,FILE='CPMT14.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.14) THEN
      OPEN (UNIT=6,FILE='CPMT15.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.15) THEN
      OPEN (UNIT=6,FILE='CPMT16.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.16) THEN
      OPEN (UNIT=6,FILE='CPMT17.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.17) THEN
      OPEN (UNIT=6,FILE='CPMT18.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      ELSE IF (NPTEST.EQ.18) THEN
      OPEN (UNIT=6,FILE='CPMT19.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
```

```
      ELSE IF (NPTEST.EQ.19) THEN
      OPEN (UNIT=6,FILE='CPMT20.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
      END IF
C     The number of COMPLETED tests is the number of PREVIOUS tests plus 1
      NCTEST=NPTEST+1
      WRITE (6,2500) SNAME,CNAME
2500  FORMAT (2A20)
      WRITE (6,2502) NCTEST,LIMB,DAY,MTH,YEAR,MCH,TIME
2502  FORMAT (6I7,F7.2)
      WRITE (6,2503) FINAT1,FINAT2,FINAT3,FINAT4
2503  FORMAT (4I4)
      WRITE (6,2505) XP,YP,ZP
      WRITE (6,2505) XQ,YQ,ZQ
      WRITE (6,2505) CNNFX,CNNFY,CNNFZ
2505  FORMAT(3F7.2)
      WRITE (6,2510) PHIX,PHIY,PHIZ,AXIS
2510  FORMAT(4F7.2)
      WRITE (6,2515) XRI,YRI,ZRI
      WRITE (6,2515) XRM,YRM,ZRM
      WRITE (6,2515) XRR,YRR,ZRR
      WRITE (6,2515) XRL,YRL,ZRL
2515  FORMAT (3F7.2)
      CLOSE (UNIT=6)
C
C     Update file TOTNO.TEST ..
      BACKSPACE 5
      WRITE (5,2520) NCTEST,SNAME,TIME,DAY,MTH,YEAR
2520  FORMAT (I4,A20,F7.2,3I7)
C
3000  CLOSE (UNIT=5)
      STOP
      END
```

APPENDIX 3.2

Program to determine node coordinates in the finger linkage

meccano.mcd

PROGRAM TAKEN FROM MECC12.MCD;

SET Z VALUES TO NOMINAL VALUE OF 1
(i.e. two dimensional planar motion only:)

$Z1 := 1 \quad Z2 := 1 \quad Z3 := 1 \quad Z4 := 1 \quad Z5 := 1 \quad Z6 := 1 \quad Z7 := 1 \quad Z8 := 1$
$Z9 := 1 \quad Z10 := 1 \quad Z11 := 1 \quad Z12 := 1 \quad Z13 := 1 \quad Z14 := 1 \quad Z15 := 1 \quad Z16 := 1$
$Z17 := 1 \quad Z18 := 1$

SET THE COORDINATES OF THE FIXED POINTS:

$X1G := 300 \quad X2G := 358.1699 \quad X3G := 361$
$Y1G := 300 \quad Y2G := 278.8299 \quad Y3G := 270$

Calculate the lengths of D12,D23,D13:

$$D12 := \sqrt{(X1G - X2G)^2 + (Y1G - Y2G)^2} \qquad D12 = 61.902$$

$$D23 := \sqrt{(X2G - X3G)^2 + (Y2G - Y3G)^2} \qquad D23 = 9.272$$

$$D13 := \sqrt{(X1G - X3G)^2 + (Y1G - Y3G)^2} \qquad D13 = 67.978$$

SET LENGTHS OF LINKS TO FIXED VALUES:

$D34 := 70 \quad D45 := 65 \quad D48 := 20 \quad D57 := 16 \quad D89 := 60 \quad D78 := 55 \quad D1012 := 16$

$D910 := 50 \quad D915 := 75 \quad D1516 := 55$

SET THE DIP JOINT LOCKING LINK TO CORRECT POSITION:

$D1314 := 18 \quad D914 := 25 \quad D913 := 25$

SET LENGTHS OF ACTUATOR ROD ATTACHMENT ROD:

$D1517 := 32 \quad D1617 := 42.5$

SET LENGTHS OF THE PHALANGES USING PRE-DETERMINED RATIOS-:

NB: Nordin & Frankel: 46, 28, 18

see table 6.2.3.(iv) in thesis also

$D26 := 52.79$
$R611over26 := 0.64103$
$R1118over26 := 0.473$

$D611 := R611over26 \cdot D26 \quad D611 = 33.84$
$D1118 := R1118over26 \cdot D26 \quad D1118 = 24.97$

ENTER DISTANCES BETWEEN LINKAGE BLOCKS AND BONE AXES:

$D26to57 := 20 \quad D611to1012 := 20 \quad D1118to16 := 16$

ENTER 'ALPHA' ANGLES IN RIGID BODIES:

alpha1 is ALPHA2667, alpha2 is ALPHA126611, alpha3 is ALPHA18111116

$ALPHA1 := 70 \qquad ALPHA2 := 60 \qquad ALPHA3 := 68$

CALCULATE THE LENGTHS BETWEEN THE SPLINT NODES AND THE FINGER JOINTS:

Body 3:

$$D67 := \frac{D26to57}{\sin\left(ALPHA1 \cdot \frac{\pi}{180}\right)} \qquad D67 = 21.284$$

$$D25 := \frac{D26to57}{\sin\left(\operatorname{atan}\left(\frac{D26to57}{D26 - D57 - D67 \cdot \cos\left(ALPHA1 \cdot \frac{\pi}{180}\right)}\right)\right)} \qquad D25 = 35.649$$

$$D612 := \frac{D611to1012}{\sin\left(ALPHA2 \cdot \frac{\pi}{180}\right)} \qquad D612 = 23.094$$

$$D1011 := \frac{D611to1012}{\sin\left(\operatorname{atan}\left(\frac{D611to1012}{D611 - D1012 - D612 \cdot \cos\left(ALPHA2 \cdot \frac{\pi}{180}\right)}\right)\right)} \qquad D1011 = 20.967$$

$SGN1 := -1 \qquad SGN2 := 1$

$SGN := \mathrm{if}(D1011 < 0, SGN1, SGN2)$

$D1011 := D1011 \cdot SGN \qquad D1011 = 20.967$

$$D1116 := \frac{D1118to16}{\sin\left(ALPHA3 \cdot \frac{\pi}{180}\right)} \qquad D1116 = 17.257$$

$$D1618 := \sqrt{D1118^2 + D1116^2 - \left(2 \cdot D1116 \cdot D1118 \cdot \cos\left(ALPHA3 \cdot \frac{\pi}{180}\right)\right)} \qquad D1618 = 24.463$$

SET THE CRANK ANGLE, TO THE VERTICAL, TO KNOWN VALUE, TO ENSURE NODE 4 HAS THE SAME COORDINATES IN BOTH FINGER9.MDX

Note that crank angle 65 degs (to the vertical) in DeMEC is equivalent to 115 degs (to the vertical) in this program; crank angle -28 degs in DeMEC is equivalent to 208 degs in this program,

USE i = 115 & CA = i..2 0 8

$i := 115 \qquad CA := i..208$

$$ALPHA433G_{CA} := CA \cdot \left(\frac{\pi}{180}\right)$$

BODY 2 (four bar linkage):

$$X4G_{CA} := \left(D34\cdot\sin\left(ALPHA433G_{CA}\right)\right) + X3G$$
$$Y4G_{CA} := \left(D34\cdot\cos\left(ALPHA433G_{CA}\right)\right) + Y3G$$

Determine the rotation of the crank wrt D23:

The vector 32 is: $I32 := (X2G - X3G)$ $\quad I32 = -2.83$

$J32 := (Y2G - Y3G)$ $\quad J32 = 8.83$

The vector 34 is: $I34_{CA} := \left(X4G_{CA} - X3G\right)$ $J34_{CA} := \left(Y4G_{CA} - Y3G\right)$

Apply scalar produc $ALPHA2334_{CA} := \mathrm{acos}\left[\dfrac{\left(I32\cdot I34_{CA}\right) + \left(J32\cdot J34_{CA}\right)}{D23\cdot D34}\right]$

Determine coordinates of point 5 wrt 3 in axis system fixed to body 2:

$$D24_{CA} := \sqrt{D34^2 + D23^2 - \left(2\cdot D23\cdot D34\cdot\cos\left(ALPHA2334_{CA}\right)\right)}$$

$$ALPHA2554_{CA} := \mathrm{acos}\left[\frac{D25^2 + D45^2 - \left(D24_{CA}\right)^2}{2\cdot D25\cdot D45}\right]$$

$$ALPHA5224_{CA} := \mathrm{acos}\left[\frac{D25^2 + \left(D24_{CA}\right)^2 - D45^2}{2\cdot D25\cdot D24_{CA}}\right]$$

$$ALPHA3224_{CA} := \mathrm{acos}\left[\frac{\left(D23^2\right) + \left(D24_{CA}\right)^2 - D34^2}{2\cdot D23\cdot D24_{CA}}\right]$$

$$R2 := \frac{D23}{D23 + D34}$$

$$M2_{CA} := ALPHA5224_{CA} + ALPHA3224_{CA}$$
$$N2_{CA} := ALPHA5224_{CA} - ALPHA3224_{CA}$$

$$ALPHA5223_{CA} := \mathrm{if}\left[R2\cdot\left(X4G_{CA} - X2G\right) + X2G \geq X3G, M2_{CA}, N2_{CA}\right]$$

$$X5b2_{CA} := D23 - D25\cdot\cos\left(ALPHA5223_{CA}\right)$$

$$Y5b2_{CA} := -D25\cdot\sin\left(ALPHA5223_{CA}\right)$$

Determine the coordinates of point 5 wrt the ground based axis system:

Rotation of body 2 wrt ground based axes:

Calculate angle PHIb2gb:

First calculate the angle of 32 to the horizontal:

The vector 32 is: $I32 := (X2G - X3G)$ $J32 := (Y2G - Y3G)$ $I32 = -2.83$

$J32 = 8.83$

The vector of the horizontal is: $I3GH := 1$

$J3GH := 0$

Apply scalar product: $$ALPHA233GH := \mathrm{acos}\left[\frac{(I32 \cdot I3GH) + (J32 \cdot J3GH)}{D23 \cdot I3GH}\right]$$

$$ALPHA233GH \cdot \left(\frac{180}{\pi}\right) = 107.771$$

$$PHIb2gb := \mathrm{if}(Y2G \geq Y3G, ALPHA233GH, -ALPHA233GH)$$

$$PHIb2gb \cdot \left(\frac{180}{\pi}\right) = 107.771$$

$$\begin{bmatrix} FRED_{CA} \\ X5G_{CA} \\ Y5G_{CA} \\ Z5G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X3G & 1 & 0 & 0 \\ Y3G & 0 & 1 & 0 \\ Z3 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb2gb) & -\sin(PHIb2gb) & 0 \\ 0 & \sin(PHIb2gb) & \cos(PHIb2gb) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X5b2_{CA} \\ Y5b2_{CA} \\ Z5 \end{bmatrix}$$

BODY 3 (rigid body):

$$AALPHA6225 := \frac{\left[D67^2 + D57^2 + (2 \cdot D57 \cdot D26) - \left(2 \cdot D57^2\right) - D26^2 - D25^2\right]}{((2 \cdot D57 \cdot D25) - (2 \cdot D26 \cdot D25))}$$

$ALPHA6225 := \mathrm{acos}(AALPHA6225)$ $\quad ALPHA6225 \cdot \left(\frac{180}{\pi}\right) = 34.126$

$ALPHA2557 := \pi - ALPHA6225$ $\quad ALPHA2557 \cdot \left(\frac{180}{\pi}\right) = 145.874$

Determine the coordinates of node 6 wrt to body 3:

$X6b3 := D26 \cdot \cos(ALPHA6225)$ $\quad X6b3 = 43.7$

$Y6b3 := D26 \cdot \sin(ALPHA6225)$ $\quad Y6b3 = 29.616$

Determine the coordinates of node 7 wrt to body 3:

$X7b3 := D57 \cdot \cos(\pi - ALPHA2557) + D25$ $\quad X7b3 = 48.894$

$Y7b3 := D57 \cdot \sin(\pi - ALPHA2557)$ $\quad Y7b3 = 8.976$

Determine the rotation of body 3 wrt ground:

$$PHIb3gb_{CA} := \mathrm{atan}\left(\frac{Y5G_{CA} - Y2G}{X5G_{CA} - X2G}\right)$$

Determine the coordinates of point 6 wrt the ground based axis system:

$$\begin{bmatrix} FRED_{CA} \\ X6G_{CA} \\ Y6G_{CA} \\ Z6G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X2G & 1 & 0 & 0 \\ Y2G & 0 & 1 & 0 \\ Z2 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb3gb_{CA}) & -\sin(PHIb3gb_{CA}) & 0 \\ 0 & \sin(PHIb3gb_{CA}) & \cos(PHIb3gb_{CA}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X6b3 \\ Y6b3 \\ Z6 \end{bmatrix}$$

Determine the coordinates of point 7 wrt the ground based axis system:

$$\begin{bmatrix} FRED_{CA} \\ X7G_{CA} \\ Y7G_{CA} \\ Z7G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X2G & 1 & 0 & 0 \\ Y2G & 0 & 1 & 0 \\ Z2 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb3gb_{CA}) & -\sin(PHIb3gb_{CA}) & 0 \\ 0 & \sin(PHIb3gb_{CA}) & \cos(PHIb3gb_{CA}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X7b3 \\ Y7b3 \\ Z7 \end{bmatrix}$$

BODY 4 (four bar linkage):

Determine coordinates of point 8 wrt 5 in axis system fixed to body 4:

Calculate angle 7554

The vector 57 is: $I57_{CA} := (X7G_{CA} - X5G_{CA})$ $\quad J57_{CA} := (Y7G_{CA} - Y5G_{CA})$

The vector 54 is: $I54_{CA} := (X4G_{CA} - X5G_{CA})$ $\quad J54_{CA} := (Y4G_{CA} - Y5G_{CA})$

Apply scalar product: $ALPHA7554_{CA} := \operatorname{acos}\left[\frac{(I57_{CA} \cdot I54_{CA}) + (J57_{CA} \cdot J54_{CA})}{D45 \cdot D57}\right]$

$$D47_{CA} := \sqrt{D45^2 + D57^2 - (2 \cdot D45 \cdot D57 \cdot \cos(ALPHA7554_{CA}))}$$

$$ALPHA4887_{CA} := \operatorname{acos}\left[\frac{D48^2 + D78^2 - (D47_{CA})^2}{2 \cdot D48 \cdot D78}\right]$$

$$ALPHA7448_{CA} := \operatorname{acos}\left[\frac{(D47_{CA})^2 + D48^2 - D78^2}{2 \cdot D47_{CA} \cdot D48}\right]$$

$$ALPHA5447_{CA} := \operatorname{acos}\left[\frac{D45^2 + (D47_{CA})^2 - D57^2}{2 \cdot D45 \cdot D47_{CA}}\right]$$

$$R4 := \frac{D45}{D45 + D57}$$

$M4_{CA} := ALPHA7448_{CA} + ALPHA5447_{CA}$ $\quad N4_{CA} := ALPHA7448_{CA} - ALPHA5447_{CA}$

$ALPHA5448_{CA} := \text{if}\left[R4 \cdot (X7G_{CA} - X4G_{CA}) + X4G_{CA} \geq X5G_{CA}, M4_{CA}, N4_{CA}\right]$

$X8b4_{CA} := D45 - (D48 \cdot \cos(ALPHA5448_{CA}))$ $\quad Y8b4_{CA} := D48 \cdot \sin(ALPHA5448_{CA})$

Determine the coordinates of point 8 wrt the ground based axis system:

Calculate angle PHIb4gb:

First calculate the angle of 57 to the vertical:

The vector 57 is: $I57_{CA} := \left(X7G_{CA} - X5G_{CA}\right)$ $J57_{CA} := \left(Y7G_{CA} - Y5G_{CA}\right)$

The vector of the vertical is: $I5G := 0$ $J5G := 1$

Apply scalar product:

$$ALPHA755G_{CA} := \mathrm{acos}\left[\frac{\left(I57_{CA} \cdot I5G\right) + \left(J57_{CA} \cdot J5G\right)}{D57 \cdot J5G}\right]$$

$$PHIb4gb_{CA} := \left(\frac{\pi}{2}\right) - ALPHA755G_{CA} - ALPHA7554_{CA}$$

$$\begin{bmatrix} FRED_{CA} \\ X8G_{CA} \\ Y8G_{CA} \\ Z8G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X5G_{CA} & 1 & 0 & 0 \\ Y5G_{CA} & 0 & 1 & 0 \\ Z2 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb4gb_{CA}\right) & -\sin\left(PHIb4gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb4gb_{CA}\right) & \cos\left(PHIb4gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X8b4_{CA} \\ Y8b4_{CA} \\ Z8 \end{bmatrix}$$

Determine the coordinates of 9, using global coordinates;

$$X9G_{CA} := \left[\frac{\left(X8G_{CA} - X4G_{CA}\right) \cdot (D48 + D89)}{D48}\right] + X4G_{CA}$$

$$Y9G_{CA} := \left[\frac{\left(Y8G_{CA} - Y4G_{CA}\right) \cdot (D48 + D89)}{D48}\right] + Y4G_{CA}$$

BODY 5 (four bar linkage with offset):

Calculate angle 7889:

The vector 87 is: $I87_{CA} := \left(X7G_{CA} - X8G_{CA}\right)$ $J87_{CA} := \left(Y7G_{CA} - Y8G_{CA}\right)$

The vector 89 is: $I89_{CA} := \left(X9G_{CA} - X8G_{CA}\right)$ $J89_{CA} := \left(Y9G_{CA} - Y8G_{CA}\right)$

Apply scalar product:

$$ALPHA7889_{CA} := \mathrm{acos}\left[\frac{\left(I87_{CA} \cdot I89_{CA}\right) + \left(J87_{CA} \cdot J89_{CA}\right)}{D78 \cdot D89}\right]$$

Calculate the length D79:

$$D79_{CA} := \sqrt{D78^2 + D89^2 - \left(2 \cdot D78 \cdot D89 \cdot \cos\left(ALPHA7889_{CA}\right)\right)}$$

Calculate angle 6779:

The vector 76 is: $I76_{CA} := \left(X6G_{CA} - X7G_{CA}\right)$ $J76_{CA} := \left(Y6G_{CA} - Y7G_{CA}\right)$

The vector 79 is: $I79_{CA} := \left(X9G_{CA} - X7G_{CA}\right)$ $J79_{CA} := \left(Y9G_{CA} - Y7G_{CA}\right)$

Apply scalar product:

$$ALPHA6779_{CA} := \operatorname{acos}\left[\frac{(I76_{CA}\cdot I79_{CA}) + (J76_{CA}\cdot J79_{CA})}{D67\cdot D79_{CA}}\right]$$

$$D69S_{CA} := D67^2 + (D79_{CA})^2 - (2\cdot D67\cdot D79_{CA}\cdot\cos(ALPHA6779_{CA})) \qquad D69_{CA} := \sqrt{D69S_{CA}}$$

$$ALPHA116612 := ALPHA2\cdot\left(\frac{\pi}{180}\right) \qquad ALPHA6121210 := \pi - ALPHA116612$$

$$D610 := \sqrt{D612^2 + D1012^2 - (2\cdot D612\cdot D1012\cdot\cos(ALPHA6121210))} \qquad D610 = 34.042$$

$$ALPHA7996_{CA} := \operatorname{acos}\left[\frac{(D69_{CA})^2 + (D79_{CA})^2 - D67^2}{2\cdot D69_{CA}\cdot D79_{CA}}\right]$$

$$ALPHA69910_{CA} := \operatorname{acos}\left[\frac{(D69_{CA})^2 + D910^2 - D610^2}{2\cdot D69_{CA}\cdot D910}\right]$$

$$R5_{CA} := \frac{D67}{D67 + D79_{CA}}$$

$$M5_{CA} := ALPHA69910_{CA} + ALPHA7996_{CA} \qquad N5_{CA} := ALPHA69910_{CA} - ALPHA7996_{CA}$$

$$ALPHA79910_{CA} := \text{if}\left[R5_{CA}\cdot(X9G_{CA} - X6G_{CA}) + X6G_{CA} \ge X7G_{CA}, M5_{CA}, N5_{CA}\right]$$

$$X10b5_{CA} := D79_{CA} - (D910\cdot\cos(ALPHA79910_{CA})) \qquad Y10b5_{CA} := D910\cdot\sin(ALPHA79910_{CA})$$

Determine the coordinates of point 10 wrt the ground based axis system:

Rotation of body 5 wrt the ground based axis system:

Calculate angle PHIb5gb: First calculate the angle of 79 to the vertical:

The vector 79 is: $I79_{CA} := (X9G_{CA} - X7G_{CA})$ $J57_{CA} := (Y9G_{CA} - Y7G_{CA})$

The vector of the vertical is: $I7G := 0$ $J7G := 1$

Apply scalar product:

$$ALPHA797G_{CA} := \operatorname{acos}\left[\frac{(I79_{CA}\cdot I7G) + (J79_{CA}\cdot J7G)}{D79_{CA}\cdot J7G}\right]$$

$$PHIb5gb_{CA} := \text{if}\left[X9G_{CA} \ge X7G_{CA}, \frac{\pi}{2} - ALPHA797G_{CA}, ALPHA797G_{CA} - \left(3\cdot\frac{\pi}{2}\right)\right]$$

$$\begin{bmatrix} FRED_{CA} \\ X10G_{CA} \\ Y10G_{CA} \\ Z10G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X7G_{CA} & 1 & 0 & 0 \\ Y7G_{CA} & 0 & 1 & 0 \\ Z7 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb5gb_{CA}) & -\sin(PHIb5gb_{CA}) & 0 \\ 0 & \sin(PHIb5gb_{CA}) & \cos(PHIb5gb_{CA}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X10b5_{CA} \\ Y10b5_{CA} \\ Z10 \end{bmatrix}$$

BODY 6 (rigid body):

$$ALPHA116610 := acos\left(\frac{D611^2 + D610^2 - D1011^2}{2 \cdot D611 \cdot D610}\right) \qquad ALPHA116610 \cdot \left(\frac{180}{\pi}\right) = 35.981$$

Determine the coordinates of node 11 wrt to body 6:

$$X11b6 := D611 \cdot \cos(ALPHA116610) \qquad X11b6 = 27.384$$

$$Y11b6 := D611 \cdot \sin(ALPHA116610) \qquad Y11b6 = 19.881$$

Determine the coordinates of node 12 wrt to body 6:

$$ALPHA106612 := \left[ALPHA2 \cdot \left(\frac{\pi}{180}\right)\right] - ALPHA116610 \qquad ALPHA106612 \cdot \left(\frac{180}{\pi}\right) = 24.019$$

$$X12b6 := D612 \cdot \cos(ALPHA106612) \quad X12b6 = 21.094$$

$$Y12b6 := -D612 \cdot \sin(ALPHA106612) \quad Y12b6 = -9.4$$

Determine the rotation of body 6 wrt ground:

$$PHIb6gb_{CA} := atan\left(\frac{Y10G_{CA} - Y6G_{CA}}{X10G_{CA} - X6G_{CA}}\right)$$

Determine the coordinates of point 11 wrt the ground based axis system:

$$\begin{bmatrix} FRED_{CA} \\ X11G_{CA} \\ Y11G_{CA} \\ Z11G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X6G_{CA} & 1 & 0 & 0 \\ Y6G_{CA} & 0 & 1 & 0 \\ Z6 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb6gb_{CA}) & -\sin(PHIb6gb_{CA}) & 0 \\ 0 & \sin(PHIb6gb_{CA}) & \cos(PHIb6gb_{CA}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X11b6 \\ Y11b6 \\ Z11 \end{bmatrix}$$

Determine the coordinates of point 12 wrt the ground based axis system:

$$\begin{bmatrix} FRED_{CA} \\ X12G_{CA} \\ Y12G_{CA} \\ Z12G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X6G_{CA} & 1 & 0 & 0 \\ Y6G_{CA} & 0 & 1 & 0 \\ Z6 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(PHIb6gb_{CA}) & -\sin(PHIb6gb_{CA}) & 0 \\ 0 & \sin(PHIb6gb_{CA}) & \cos(PHIb6gb_{CA}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X12b6 \\ Y12b6 \\ Z12 \end{bmatrix}$$

BODY 7 (fixed joints to stiffen DIP joint):

$$ALPHA109915 := acos\left(\frac{D913^2 + D914^2 - D1314^2}{2 \cdot D913 \cdot D914}\right) \qquad ALPHA109915 \cdot \left(\frac{180}{\pi}\right) = 42.2$$

$$D1015 := \sqrt{D910^2 + D915^2 - (2 \cdot D910 \cdot D915 \cdot \cos(ALPHA109915))} \qquad D1015 = 50.685$$

$$ALPHA9151510 := acos\left[\frac{(D1015)^2 + D915^2 - D910^2}{2 \cdot D1015 \cdot D915}\right] \qquad ALPHA9151510 \cdot \left(\frac{180}{\pi}\right) = 41.502$$

$$D911_{CA} := \sqrt{(X9G_{CA} - X11G_{CA})^2 + (Y9G_{CA} - Y11G_{CA})^2}$$

$$ALPHA109911_{CA} := \operatorname{acos}\left[\frac{D910^2 + \left(D911_{CA}\right)^2 - D1011^2}{2 \cdot D910 \cdot D911_{CA}}\right]$$

$$ALPHA119915_{CA} := ALPHA109911_{CA} + ALPHA109915$$

$$D1115_{CA} := \sqrt{\left(D911_{CA}\right)^2 + D915^2 - \left(2 \cdot D911_{CA} \cdot D915 \cdot \cos\left(ALPHA119915_{CA}\right)\right)}$$

$$ALPHA10151511_{CA} := \operatorname{acos}\left[\frac{(D1015)^2 + \left(D1115_{CA}\right)^2 - D1011^2}{2 \cdot D1115_{CA} \cdot D1015}\right]$$

$$ALPHA11151516_{CA} := \operatorname{acos}\left[\frac{\left(D1115_{CA}\right)^2 + D1516^2 - D1116^2}{2 \cdot D1115_{CA} \cdot D1516}\right]$$

$$ALPHA10151516_{CA} := ALPHA10151511_{CA} + ALPHA11151516_{CA}$$

$$D1016_{CA} := \sqrt{(D1015)^2 + D1516^2 - \left(2 \cdot D1015 \cdot D1516 \cdot \cos\left(ALPHA10151516_{CA}\right)\right)}$$

$$ALPHA1510109 := \operatorname{acos}\left(\frac{D1015^2 + D910^2 - D915^2}{2 \cdot D1015 \cdot D910}\right)$$

$$ALPHA15101016_{CA} := \operatorname{acos}\left[\frac{\left(D1016_{CA}\right)^2 + D1015^2 - D1516^2}{2 \cdot D1016_{CA} \cdot D1015}\right]$$

$$ALPHA10111116_{CA} := \operatorname{acos}\left[\frac{D1011^2 + D1116^2 - \left(D1016_{CA}\right)^2}{2 \cdot D1011 \cdot D1116}\right]$$

$$ALPHA10111118_{CA} := ALPHA10111116_{CA} + ALPHA3 \cdot \left(\frac{\pi}{180}\right)$$

$$ALPHA9101015 := \operatorname{acos}\left(\frac{D910^2 + D1015^2 - D915^2}{2 \cdot D910 \cdot D1015}\right)$$

$$ALPHA9101016_{CA} := (2 \cdot \pi) - \left(ALPHA9101015 + ALPHA15101016_{CA}\right)$$

$$D1018_{CA} := \sqrt{D1011^2 + D1118^2 - \left(2 \cdot D1011 \cdot D1118 \cdot \cos\left(ALPHA10111118_{CA}\right)\right)}$$

$$ALPHA16101018_{CA} := \operatorname{acos}\left[\frac{\left(D1016_{CA}\right)^2 + \left(D1018_{CA}\right)^2 - D1618^2}{2 \cdot D1016_{CA} \cdot D1018_{CA}}\right]$$

$$ALPHA9101018_{CA} := (2 \cdot \pi) - \left(ALPHA9101015 + ALPHA15101016_{CA} + ALPHA16101018_{CA}\right)$$

$$ALPHA16151517 := \operatorname{acos}\left(\frac{D1516^2 + D1517^2 - D1617^2}{2 \cdot D1516 \cdot D1517}\right)$$

$$ALPHA9151517_{CA} := ALPHA9151510 + ALPHA10151511_{CA} + ALPHA11151516_{CA} + ALPHA16151517$$

$$ALPHA10151517_{CA} := ALPHA9151517_{CA} - ALPHA9151510$$

$$D1017_{CA} := \sqrt{(D1015)^2 + D1517^2 - \left(2 \cdot D1015 \cdot D1517 \cdot \cos\left(ALPHA10151517_{CA}\right)\right)}$$

$$D917_{CA} := \sqrt{D915^2 + D1517^2 - \left(2 \cdot D915 \cdot D1517 \cdot \cos\left(ALPHA9151517_{CA}\right)\right)}$$

$$ALPHA9101017_{CA} := \mathrm{acos}\left[\frac{D910^2 + \left(D1017_{CA}\right)^2 - \left(D917_{CA}\right)^2}{2 \cdot D910 \cdot D1017_{CA}}\right]$$

$$ALPHA10151517_{CA} := \mathrm{acos}\left[\frac{D1015^2 + D1517^2 - \left(D1017_{CA}\right)^2}{2 \cdot D1015 \cdot D1517}\right]$$

$$D1014 := \sqrt{D910^2 + D914^2 - (2 \cdot D910 \cdot D914 \cdot \cos(ALPHA109915))} \qquad D1014 = 35.679$$

$$ALPHA9101014 := \mathrm{acos}\left(\frac{D910^2 + D1014^2 - D914^2}{2 \cdot D910 \cdot D1014}\right) \qquad ALPHA9101014 \cdot \left(\frac{180}{\pi}\right) = 28.078$$

$$X15b7 := D1015 \cdot \cos(ALPHA9101015) \qquad X15b7 = -5.56$$

$$Y15b7 := D1015 \cdot \sin(ALPHA9101015) \qquad Y15b7 = 50.379$$

$$X14b7 := D1014 \cdot \cos(ALPHA9101014) \qquad X14b7 = 31.48$$

$$Y14b7 := D1014 \cdot \sin(ALPHA9101014) \qquad Y14b7 = 16.793$$

$$X16b7_{CA} := D1016_{CA} \cdot \cos\left(ALPHA9101016_{CA}\right)$$

$$SIGN1 := 1$$

$$SIGN2 := -1$$

$$SIGN := \mathrm{if}(ALPHA109915 \geq 0.767945, SIGN1, SIGN2)$$

$$Y16b7_{CA} := D1016_{CA} \cdot SIGN \cdot \sin\left(ALPHA9101016_{CA}\right)$$

$$X18b7_{CA} := D1018_{CA} \cdot \cos\left(ALPHA9101018_{CA}\right)$$

$$Y18b7_{CA} := -D1018_{CA} \cdot \sin\left(ALPHA9101018_{CA}\right)$$

$$X17b7_{CA} := D1017_{CA} \cdot \cos\left(ALPHA9101017_{CA}\right)$$

$$Y17b7_{CA} := D1017_{CA} \cdot \sin\left(ALPHA9101017_{CA}\right)$$

Calculate angle PHIb7gb:

First calculate the angle of 109 to the vertical:

The vector 109 is: $I109_{CA} := \left(X9G_{CA} - X10G_{CA}\right)$ $\qquad J109_{CA} := \left(Y9G_{CA} - Y10G_{CA}\right)$

The vector of the vertical is: $I10G := 0$ $\qquad J10G := 1$

Apply scalar product: $$ALPHA91010G_{CA} := \mathrm{acos}\left[\frac{\left(I109_{CA} \cdot I10G\right) + \left(J109_{CA} \cdot J10G\right)}{D910 \cdot J10G}\right]$$

$$PHIb7gb_{CA} := \mathrm{if}\left[X9G_{CA} \geq X10G_{CA}, \left(\frac{\pi}{2}\right) - ALPHA91010G_{CA}, \left(\frac{\pi}{2}\right) + ALPHA91010G_{CA}\right]$$

Determine the coordinates of 13, 14, 15, 16 & 17 using global coordinates;

$$\begin{bmatrix} FRED_{CA} \\ X15G_{CA} \\ Y15G_{CA} \\ Z15G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X10G_{CA} & 1 & 0 & 0 \\ Y10G_{CA} & 0 & 1 & 0 \\ Z10 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb7gb_{CA}\right) & -\sin\left(PHIb7gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb7gb_{CA}\right) & \cos\left(PHIb7gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X15b7 \\ Y15b7 \\ Z13 \end{bmatrix}$$

$$\begin{bmatrix} FRED_{CA} \\ X14G_{CA} \\ Y14G_{CA} \\ Z14G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X10G_{CA} & 1 & 0 & 0 \\ Y10G_{CA} & 0 & 1 & 0 \\ Z10 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb7gb_{CA}\right) & -\sin\left(PHIb7gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb7gb_{CA}\right) & \cos\left(PHIb7gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X14b7 \\ Y14b7 \\ Z14 \end{bmatrix}$$

$$\begin{bmatrix} FRED_{CA} \\ X16G_{CA} \\ Y16G_{CA} \\ Z16G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X10G_{CA} & 1 & 0 & 0 \\ Y10G_{CA} & 0 & 1 & 0 \\ Z10 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb7gb_{CA}\right) & -\sin\left(PHIb7gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb7gb_{CA}\right) & \cos\left(PHIb7gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X16b7_{CA} \\ Y16b7_{CA} \\ Z16 \end{bmatrix}$$

$$\begin{bmatrix} FRED_{CA} \\ X18G_{CA} \\ Y18G_{CA} \\ Z18G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X10G_{CA} & 1 & 0 & 0 \\ Y10G_{CA} & 0 & 1 & 0 \\ Z10 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb7gb_{CA}\right) & -\sin\left(PHIb7gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb7gb_{CA}\right) & \cos\left(PHIb7gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X18b7_{CA} \\ Y18b7_{CA} \\ Z18 \end{bmatrix}$$

$$\begin{bmatrix} FRED_{CA} \\ X17G_{CA} \\ Y17G_{CA} \\ Z17G_{CA} \end{bmatrix} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ X10G_{CA} & 1 & 0 & 0 \\ Y10G_{CA} & 0 & 1 & 0 \\ Z10 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(PHIb7gb_{CA}\right) & -\sin\left(PHIb7gb_{CA}\right) & 0 \\ 0 & \sin\left(PHIb7gb_{CA}\right) & \cos\left(PHIb7gb_{CA}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ X17b7_{CA} \\ Y17b7_{CA} \\ Z17 \end{bmatrix}$$

$$X13G_{CA} := X9G_{CA} - \left[\left(X9G_{CA} - X10G_{CA}\right) \cdot \frac{D913}{D910}\right] \qquad Y13G_{CA} := Y9G_{CA} + \left[\left(Y10G_{CA} - Y9G_{CA}\right) \cdot \frac{D913}{D910}\right]$$

CALCULATE THE FINGER JOINT ANGLES

MCP Joint:

The vector 26 is: $I26_{CA} := \left(X6G_{CA} - X2G\right)$ $J26_{CA} := \left(Y6G_{CA} - Y2G\right)$

The vector 21 is: $I21 := (X1G - X2G)$ $J21 := (Y1G - Y2G)$

Apply scalar product: $ALPHAMCP_{CA} := \operatorname{acos}\left[\frac{\left(I26_{CA} \cdot I21\right) + \left(J26_{CA} \cdot J21\right)}{D26 \cdot D12}\right]$

PIP Joint:

The vector 611 is: $I611_{CA} := \left(X11G_{CA} - X6G_{CA}\right)$ $J611_{CA} := \left(Y11G_{CA} - Y6G_{CA}\right)$

The vector 62 is: $I62_{CA} := \left(X2G - X6G_{CA}\right)$ $J62_{CA} := \left(Y2G - Y6G_{CA}\right)$

Apply scalar product: $ALPHAPIP_{CA} := acos\left[\frac{(I611_{CA} \cdot I62_{CA}) + (J611_{CA} \cdot J62_{CA})}{D611 \cdot D26}\right]$

DIP Joint:

The vector 1118 is: $I1118_{CA} := (X18G_{CA} - X11G_{CA})$ $J1118_{CA} := (Y18G_{CA} - Y11G_{CA})$

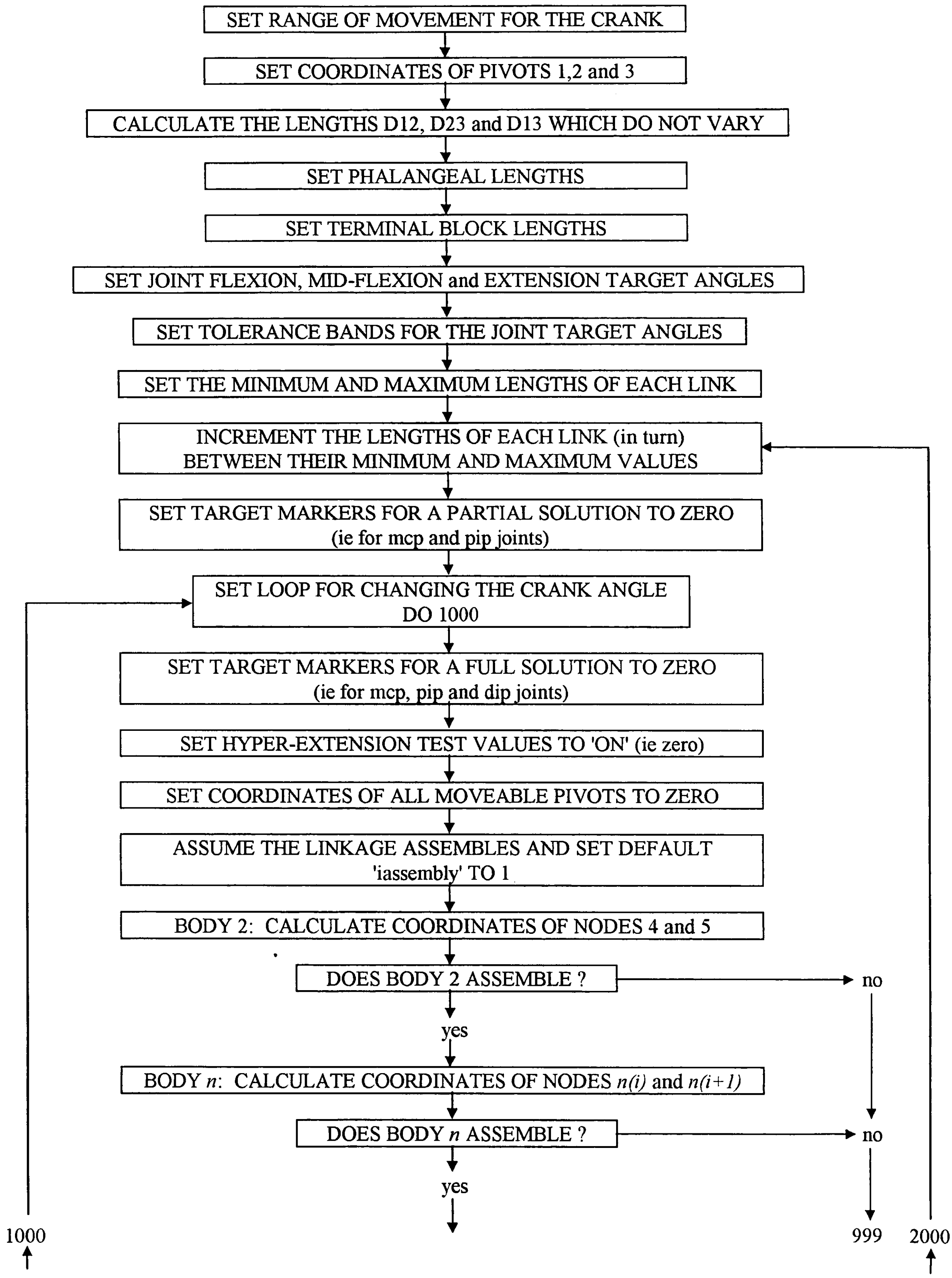
The vector 118 is: $I116_{CA} := (X6G_{CA} - X11G_{CA})$ $J116_{CA} := (Y6G_{CA} - Y11G_{CA})$

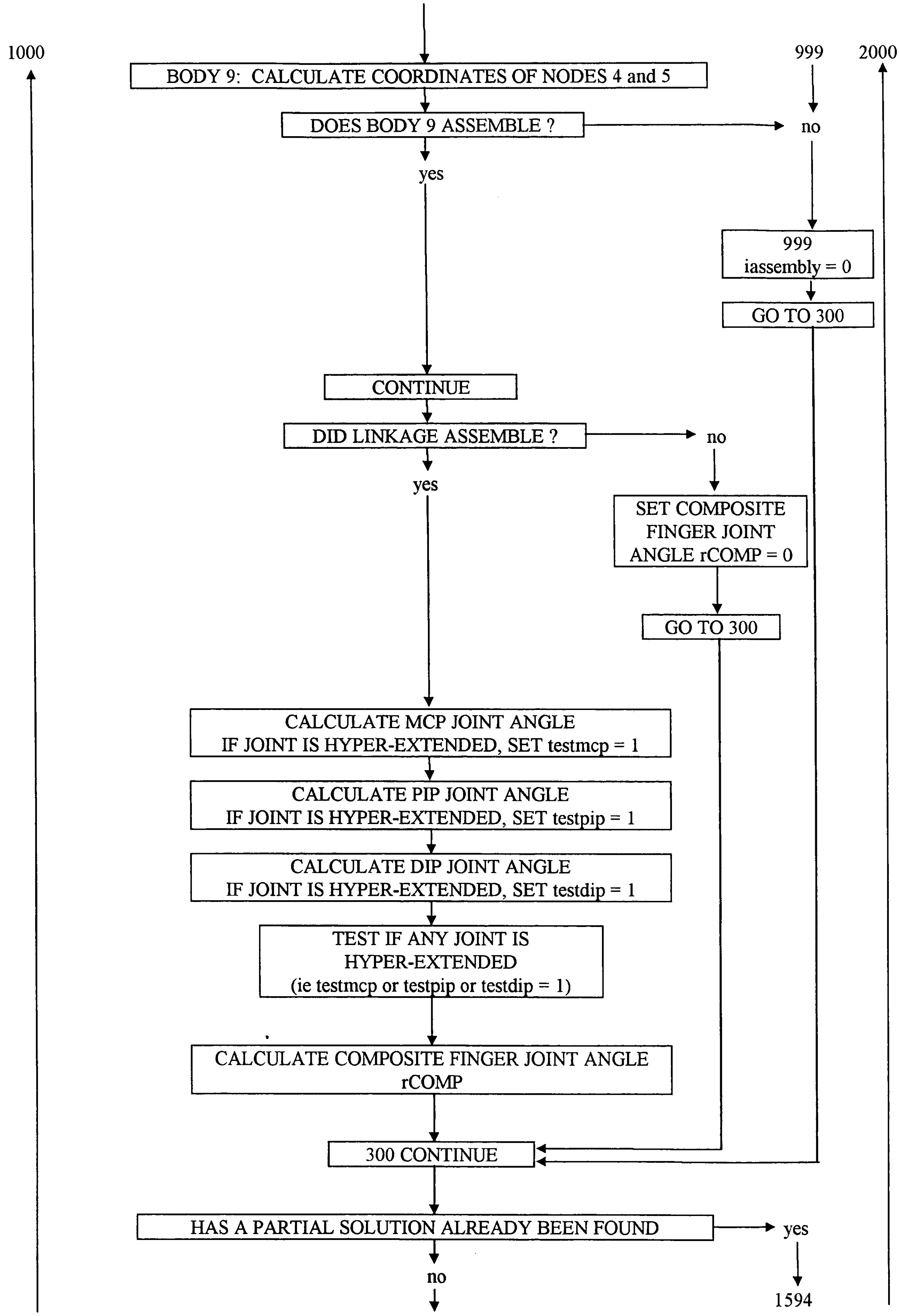
Apply scalar product: $ALPHADIP_{CA} := acos\left[\frac{(I1118_{CA} \cdot I116_{CA}) + (J1118_{CA} \cdot J116_{CA})}{D611 \cdot D1118}\right]$

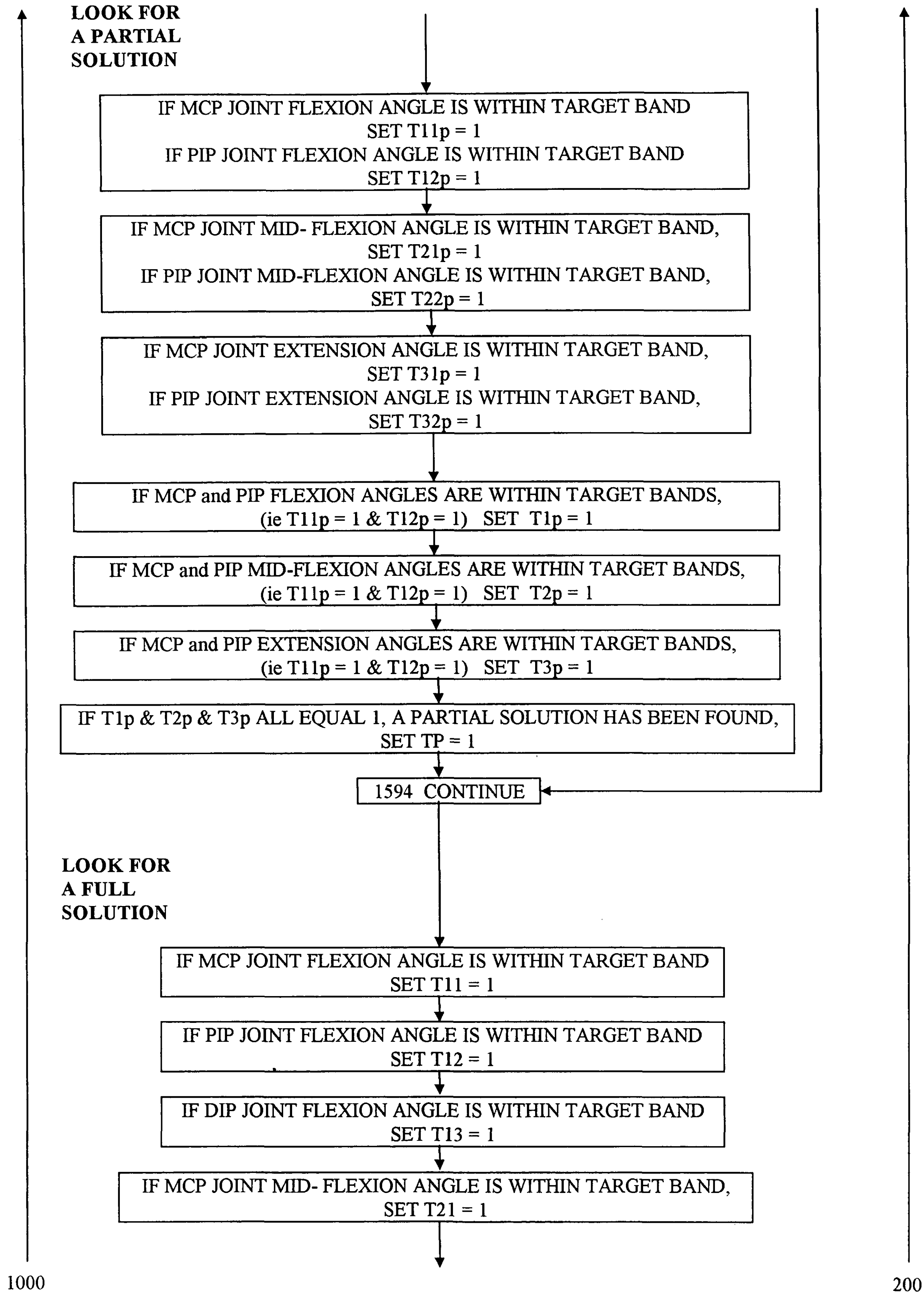
$$ALPHAMCP_{CA} := \sqrt{\left[ALPHAMCP_{CA} \cdot \left(\frac{180}{\pi}\right) - 180\right]^2} \qquad ALPHAPIP_{CA} := \sqrt{\left[ALPHAPIP_{CA} \cdot \left(\frac{180}{\pi}\right) - 180\right]^2}$$

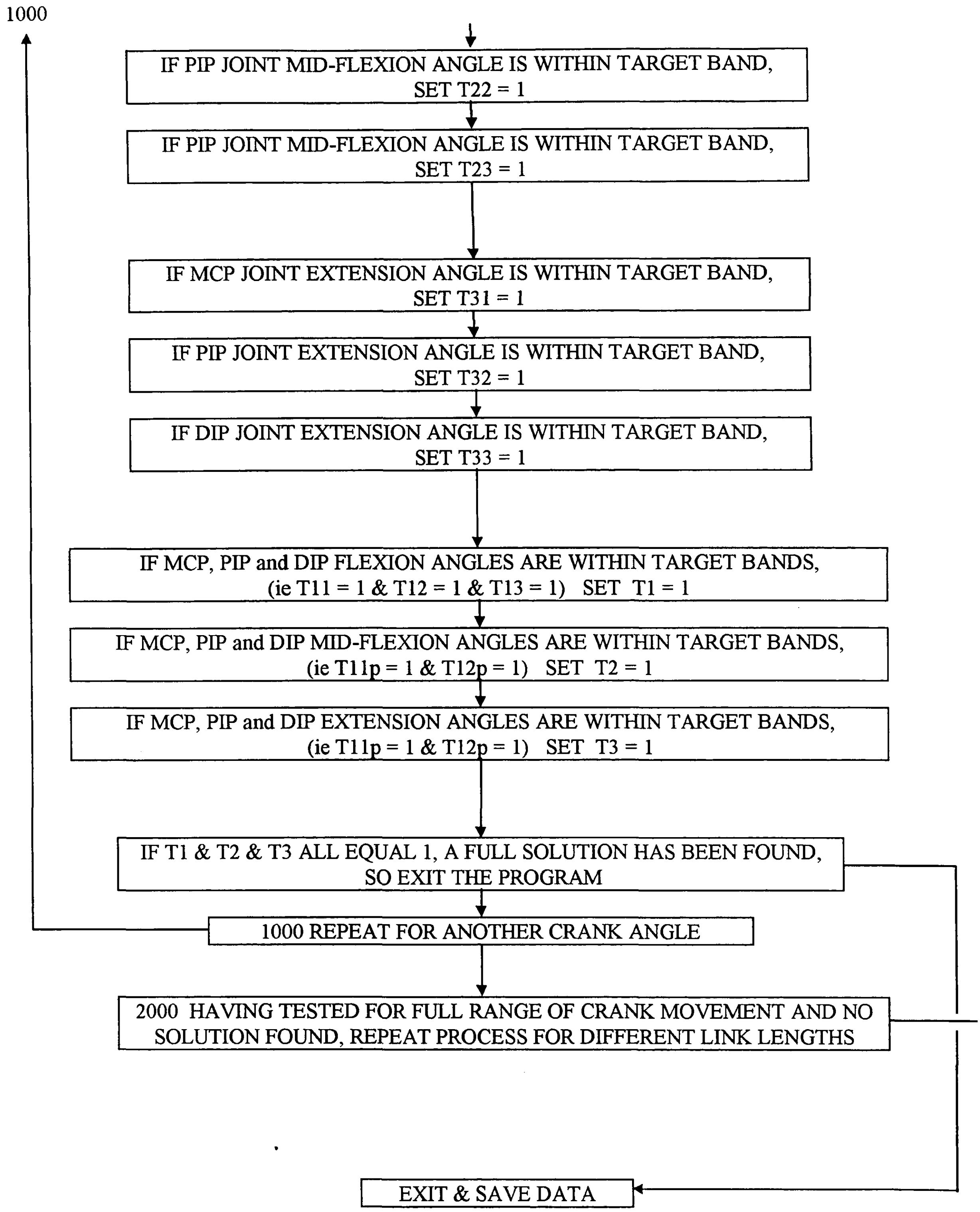
$$ALPHADIP_{CA} := \sqrt{\left[ALPHADIP_{CA} \cdot \left(\frac{180}{\pi}\right) - 180\right]^2}$$

Flow chart for program OPTALL.FOR, to determine the optimum lengths and orientations of the links in the finger linkage




1000
999
2000
BODY 9: CALCULATE COORDINATES OF NODES 4 and 5
DOES BODY 9 ASSEMBLE ?
no
yes
999
iassembly = 0
GO TO 300
CONTINUE
DID LINKAGE ASSEMBLE ?
no
yes
SET COMPOSITE FINGER JOINT ANGLE rCOMP = 0
GO TO 300
CALCULATE MCP JOINT ANGLE
IF JOINT IS HYPER-EXTENDED, SET testmcp = 1
CALCULATE PIP JOINT ANGLE
IF JOINT IS HYPER-EXTENDED, SET testpip = 1
CALCULATE DIP JOINT ANGLE
IF JOINT IS HYPER-EXTENDED, SET testdip = 1
TEST IF ANY JOINT IS HYPER-EXTENDED
(ie testmcp or testpip or testdip = 1)
CALCULATE COMPOSITE FINGER JOINT ANGLE rCOMP
300 CONTINUE
HAS A PARTIAL SOLUTION ALREADY BEEN FOUND
yes
1594
no


LOOK FOR
A PARTIAL
SOLUTION
IF MCP JOINT FLEXION ANGLE IS WITHIN TARGET BAND
SET T11p = 1
IF PIP JOINT FLEXION ANGLE IS WITHIN TARGET BAND
SET T12p = 1
IF MCP JOINT MID- FLEXION ANGLE IS WITHIN TARGET BAND,
SET T21p = 1
IF PIP JOINT MID-FLEXION ANGLE IS WITHIN TARGET BAND,
SET T22p = 1
IF MCP JOINT EXTENSION ANGLE IS WITHIN TARGET BAND,
SET T31p = 1
IF PIP JOINT EXTENSION ANGLE IS WITHIN TARGET BAND,
SET T32p = 1
IF MCP and PIP FLEXION ANGLES ARE WITHIN TARGET BANDS,
(ie T11p = 1 & T12p = 1) SET T1p = 1
IF MCP and PIP MID-FLEXION ANGLES ARE WITHIN TARGET BANDS,
(ie T11p = 1 & T12p = 1) SET T2p = 1
IF MCP and PIP EXTENSION ANGLES ARE WITHIN TARGET BANDS,
(ie T11p = 1 & T12p = 1) SET T3p = 1
IF T1p & T2p & T3p ALL EQUAL 1, A PARTIAL SOLUTION HAS BEEN FOUND,
SET TP = 1
1594 CONTINUE
LOOK FOR
A FULL
SOLUTION
IF MCP JOINT FLEXION ANGLE IS WITHIN TARGET BAND
SET T11 = 1
IF PIP JOINT FLEXION ANGLE IS WITHIN TARGET BAND
SET T12 = 1
IF DIP JOINT FLEXION ANGLE IS WITHIN TARGET BAND
SET T13 = 1
IF MCP JOINT MID- FLEXION ANGLE IS WITHIN TARGET BAND,
SET T21 = 1
1000
200


1000
IF PIP JOINT MID-FLEXION ANGLE IS WITHIN TARGET BAND, SET T22 = 1
IF PIP JOINT MID-FLEXION ANGLE IS WITHIN TARGET BAND, SET T23 = 1
IF MCP JOINT EXTENSION ANGLE IS WITHIN TARGET BAND, SET T31 = 1
IF PIP JOINT EXTENSION ANGLE IS WITHIN TARGET BAND, SET T32 = 1
IF DIP JOINT EXTENSION ANGLE IS WITHIN TARGET BAND, SET T33 = 1
IF MCP, PIP and DIP FLEXION ANGLES ARE WITHIN TARGET BANDS, (ie T11 = 1 & T12 = 1 & T13 = 1) SET T1 = 1
IF MCP, PIP and DIP MID-FLEXION ANGLES ARE WITHIN TARGET BANDS, (ie T11p = 1 & T12p = 1) SET T2 = 1
IF MCP, PIP and DIP EXTENSION ANGLES ARE WITHIN TARGET BANDS, (ie T11p = 1 & T12p = 1) SET T3 = 1
IF T1 & T2 & T3 ALL EQUAL 1, A FULL SOLUTION HAS BEEN FOUND, SO EXIT THE PROGRAM
1000 REPEAT FOR ANOTHER CRANK ANGLE
2000 HAVING TESTED FOR FULL RANGE OF CRANK MOVEMENT AND NO SOLUTION FOUND, REPEAT PROCESS FOR DIFFERENT LINK LENGTHS
EXIT & SAVE DATA

(phd\flowcht)

Program listing for OPTALL.FOR, used to determine the optimum lengths and orientations of the links in the finger linkage

```
C       OPTALL.FOR
C
C       PROGRAM BASED UPON OPT1G.FOR, AND USED TO TEST 'BIG ONE'
C       IT DOES NOT CHECK FOR CONTINUOUS FLEXION OF THE FINGER JOINTS
C       BEFORE RUNNING THIS PROGRAM, ALTER:
C             (i) the range of movement of the crank
C             (ii) the tolerance bands for the target, and possibly;
C             (iii) the flexion, mid-flexion and extension targets
C
        INTEGER COUNT,TP,TF
              COUNT = 0
              PI=3.1415927
              TEST = 1
              TP=0
              TF=0
C
C       SET THE RANGE OF THE CRANK MOVEMENT (between 'start' and 'finish')
C       THIS WILL HAVE TO BE ALTERED FOR DIFFERENT TESTS:
              CS=30
              CF=130
C
C       SET THE COORDINATES OF THE FIXED POINTS
C
        X1G=300
        Y1G=300
        X2G=358.1699
        Y2G=278.8299
        X3G=338.7798
        Y3G=272.05
C
C       CALCULATE LENGTHS WHICH WILL NOT VARY:
        D12=SQRT((X1G-X2G)**2+(Y1G-Y2G)**2)
        D23=SQRT((X2G-X3G)**2+(Y2G-Y3G)**2)
        D13=SQRT((X1G-X3G)**2+(Y1G-Y3G)**2)
C
C       PHALANGEAL LENGTHS:
        D26=44.399
        D611=26.796
        D1117=24.564
C
C       TERMINAL BLOCK LENGTHS:
        D57=16.008
        D1012=16.011
        D25=30.32
        D67=18.432
        D610=18.97
        D1112=18.628
        D1116=14.32
        D1617=21.399
C
C       SET TARGETS:
C       Full finger flexion;
                      TMCPf=75
                      TPIPf=110
                      TDIPf=70
```

```
C       Mid-flexion;
                    TMCPm=55
                    TPIPm=70
                    TDIPm=45
C       Full finger extension;
                    TMCPe=0
                    TPIPe=0
                    TDIPe=0
C
C       SET TOLERANCE BANDS (ie +/- values) FOR THE TARGETS
C       THESE VALUES WILL HAVE TO BE ALTERED:
                    BANDMCP = 10
                    BANDPIP = 10
                    BANDDIP = 10
C
C       SET THE MINIMUM AND MAXIMUM LENGTHS OF THE LINKS;
C
              D34MIN   = 20
              D34MAX   = 32
                    D34STEP   = 4
              D45MIN   = 15
              D45MAX   = 33
                    D45STEP   = 2
              D48MIN   = 15
              D48MAX   = 33
                    D48STEP   = 1
              D78MIN   = 15
              D78MAX   = 33
                    D78STEP   = 2
              D89MIN   = 36
              D89MAX   = 48
                    D89STEP   = 1
              D910MIN  = 15
              D910MAX  = 39
                    D910STEP  = 3
              D913MIN  = 36
              D913MAX  = 52
                    D913STEP  = 4
              D1213MIN = 15
              D1213MAX = 35
                    D1213STEP = 4
              D1315MIN = 30
              D1315MAX = 50
                    D1315STEP = 4
              D1516MIN = 25
              D1516MAX = 45
                    D1516STEP = 5
C
C       CALCULATE THE RUN TIME OF THE PROGRAM ON THE MAINFRAME,
C       ASSUMING THE TARGETS ARE NOT FOUND;
              L1  = ((D34MAX-D34MIN)/D34STEP) + 1
              L2  = ((D45MAX-D45MIN)/D45STEP) + 1
              L3  = ((D48MAX-D48MIN)/D48STEP) + 1
              L4  = ((D78MAX-D78MIN)/D78STEP) + 1
              L5  = ((D89MAX-D89MIN)/D89STEP) + 1
              L6  = ((D910MAX-D910MIN)/D910STEP) + 1
              L7  = ((D913MAX-D913MIN)/D913STEP) + 1
              L8  = ((D1213MAX-D1213MIN)/D1213STEP) + 1
              L9  = ((D1315MAX-D1315MIN)/D1315STEP) + 1
              L10 = ((D1516MAX-D1516MIN)/D1516STEP) + 1
```

```
C
C        The calculations below are based on 50 crank positions. The mainframe requires 1 minute for 825
C        crank cycles if printing the number of crank cycles to the screen and 920 if not printing PC
requires C        1 minute for 360 crank cycles if printing the number of crank cycles to the screen and 372
if not
C        printing
C
         WRITE (*,330)
330      FORMAT (3X,'Type <1> if running on the mainframe, <2> for PC')
         READ (*,331) iMACHINE
331      FORMAT (I1)
               IF (iMACHINE.EQ.1) AVT = 825*((CF-CS)/50)
               IF (iMACHINE.EQ.2) AVT = 360*((CF-CS)/50)
C        NUMBER OF CRANK CYCLES;
               rNCC1 = L1*L2*L3*L4
               rNCC2 = L5*L6*L7*L8*L9*L10
               rNCC = rNCC1*rNCC2

               RUNTIMEm = rNCC/AVT
         WRITE (*,332) RUNTIMEm
332      FORMAT (3X,'The estimated run time is ',F20.2,' minutes')

               RUNTIMEh = rNCC/(AVT*60)
         WRITE (*,333) RUNTIMEh
333      FORMAT (3X,'The estimated run time is ',F20.2,' hours')

               RUNTIMEd=rNCC/(AVT*60*24)
         WRITE (*,334) RUNTIMEd
334      FORMAT (3X,'The estimated run time is ',F20.2,' days')

               RUNTIMEmn=rNCC/(AVT*60*24*31)
         WRITE (*,336) RUNTIMEmn
336      FORMAT (3X,'The estimated run time is ',F20.2,' months')

               RUNTIMEy=rNCC/(AVT*60*24*31*12)
         WRITE (*,3361) RUNTIMEy
3361     FORMAT (3X,'The estimated run time is ',F20.2,' years')

         WRITE (*,337) rNCC
337      FORMAT (3X,'The maximum number of crank cycles is',F15.0)
         WRITE (*,338)
338      FORMAT (' ')
         WRITE (*,339)
339      FORMAT (3X,'DO NOT FORGET TO DELETE "optres*.dat" !!!!')
         WRITE (*,338)
         WRITE (*,341)
341      FORMAT (3X,'PRESS <RETURN> TO CONTINUE ....')
         READ (*,342) RIN
342      FORMAT (F2.1)
C
         DO 11000  D34 = D34MIN,D34MAX,D34STEP
         DO 10000  D45 = D45MIN,D45MAX,D45STEP
         DO 9000   D48 = D48MIN,D48MAX,D48STEP
         DO 8000   D78 = D78MIN,D78MAX,D78STEP
         DO 7000   D89 = D89MIN,D89MAX,D89STEP
         DO 6000  D910 = D910MIN,D910MAX,D910STEP
         DO 5000  D913 = D913MIN,D913MAX,D913STEP
         DO 4000 D1213 = D1213MIN,D1213MAX,D1213STEP
         DO 3000 D1315 = D1315MIN,D1315MAX,D1315STEP
         DO 2000 D1516 = D1516MIN,D1516MAX,D1516STEP
```

```
C
C       SET (and reset) TARGET MARKERS FOR A PARTIAL SOLUTION (mcp and pip joints only)
C       TO ZERO IF A PARTIAL SOLUTION HAS NOT ALREADY BEEN FOUND:
              IF (TP.EQ.1) GO TO 1112
              T11p=0
              T12p=0
              T1p=0
              T21p=0
              T22p=0
              T2p=0
              T31p=0
              T32p=0
              T3p=0
1112    CONTINUE
C
C       SET (and reset) TARGET MARKERS FOR A FULL SOLUTION (all three finger joints)
C       TO ZERO:
              T11 = 0
              T12 = 0
              T13 = 0
              T1  = 0
              T21 = 0
              T22 = 0
              T23 = 0
              T2  = 0
              T31 = 0
              T32 = 0
              T33 = 0
              T3  = 0
C
C       SET UP LOOP FOR THE CRANK ANGLE:
              DO 1000 CA=CS,CF
              ALPHA2334=CA*PI/180
C       STEP=CA-CS
C
C       WRITE (*,6778) TP,TF
C6778   FORMAT (EX,'TP = ',I2,3X,'TF = 'I2)
C       ASSUME HYPER-EXTENSION AND SET (and reset) TEST VALUES TO ZERO,
C       MEANING HYPER-EXTENDED
              TESTMCP=0
              TESTPIP=0
              TESTDIP=0
C
C       SET (and reset) COORDINATES OF MOVEABLE PIVOTS TO ZERO
              X4G=0
              X5G=0
              X6G=0
              X7G=0
              X8G=0
              X9G=0
              X10G=0
              X11G=0
              X12G=0
              X13G=0
              X14G=0
              X15G=0
              X16G=0
              X17G=0
C
C       Assume the linkage assembles and set the default to '1':
```

```
              IASSEMBLY = 1
C
C       BODY2:
C        WRITE (*,182)
C182    FORMAT (10X,'got to the beginning of body 2')
        rI32=X2G-X3G
        rJ32=Y2G-Y3G
        rI3GV=0
        rJ3GV=1
        TEMP233GV=((rI32*rI3GV)+(rJ32*rJ3GV))/(D23*rJ3GV)
C        check for assembly of body 2;
              if ((TEMP233GV**2).lt.1) go to 21
              iassembly = 0
              go to 999
21      ALPHA233GV=ACOS(TEMP233GV)
        ALPHA433G=ALPHA233GV+ALPHA2334
        X4G=(D34*SIN(ALPHA433G))+X3G
        Y4G=(D34*COS(ALPHA433G))+Y3G
C       check for assembly of body 2;
        if(((D34**2)+(D23**2)).gt.(2*D23*D34*COS(ALPHA2334)))go to 22
              iassembly = 0
              go to 999
22      D24=SQRT((D34**2)+(D23**2)-(2*D23*D34*COS(ALPHA2334)))
C       check for assembly of body 2;
              if (D24.LT.(D25+D45)) go to 23
              iassembly = 0
              go to 999
23      TEMP2554=((D25**2)+(D45**2)-(D24**2))/(2*D25*D45)
C       check for assembly of body 2;
              if ((TEMP2554**2).lt.1) go to 24
              iassembly = 0
              go to 999
24      ALPHA2554=ACOS(TEMP2554)
        TEMP5224=((D25**2)+(D24**2)-(D45**2))/(2*D25*D24)
C       check for assembly of body 2;
              if ((TEMP5224**2).lt.1) go to 25
              iassembly = 0
              go to 999
25      ALPHA5224=ACOS(TEMP5224)
        TEMP3224=((D23**2)+(D24**2)-(D34**2))/(2*D23*D24)
C       check for assembly of body 2;
              if ((TEMP3224**2).lt.1) go to 26
              iassembly = 0
              go to 999
26      ALPHA3224=ACOS(TEMP3224)
        R2=D23/(D23+D34)
        rM2=ALPHA5224+ALPHA3224
        rN2=ALPHA5224-ALPHA3224
        IF (((R2*(X4G-X2G))+X2G).GE.X3G) ALPHA5223=rM2
        IF (((R2*(X4G-X2G))+X2G).LT.X3G) ALPHA5223=rN2
        X5b2=D23-(D25*COS(ALPHA5223))
        Y5b2=-(D25*SIN(ALPHA5223))
        rI32=X2G-X3G
        rJ32=Y2G-Y3G
        rI3GH=1
        rJ3GH=0
        TEMP233GH=((rI32*rI3GH)+(rJ32*rJ3GH))/(D23*rI3GH)
C       check for assembly of body 2:
              if ((TEMP233GH**2).lt.1) go to 27
              iassembly = 0
```

```
                go to 999
27          ALPHA233GH=ACOS(TEMP233GH)
            IF (Y2G.GE.Y3G) PHIb2gb=ALPHA233GH
            IF (Y2G.LT.Y3G) PHIb2gb=-ALPHA233GH
            X5G=X3G+((X5b2*COS(PHIb2gb))-(Y5b2*SIN(PHIb2gb)))
            Y5G=Y3G+((X5b2*SIN(PHIb2gb))+(Y5b2*COS(PHIb2gb)))
C           BODY 3:
C            WRITE (*,183)
C183        FORMAT (10X,'got to the beginning of body 3')
            U1=(D67**2)+(D57**2)+(2*D57*D26)-(2*D57**2)-(D26**2)-(D25**2)
            U2=(2*D57*D25)-(2*D26*D25)
            TEMP6225=(U1/U2)
C           check for assembly of body 3:
                if ((TEMP6225**2).lt.1) go to 31
                iassembly = 0
                go to 999
31          ALPHA6225=ACOS(TEMP6225)
            TEMP2667=(D26-(D25*COS(ALPHA6225))-D57)/D67
C           check for assembly of body 3:
                if ((TEMP2667**2).lt.1) go to 32
                iassembly = 0
                go to 999
32          ALPHA2667=ACOS(TEMP2667)
            ALPHA2557=PI-ALPHA6225
            X6b3=D26*COS(ALPHA6225)
            Y6b3=D26*SIN(ALPHA6225)
            X7b3=D57*COS(PI-ALPHA2557)+D25
            Y7b3=D57*SIN(PI-ALPHA2557)
            PHIb3gb=ATAN((Y5G-Y2G)/(X5G-X2G))
            X6G=X2G+(X6b3*COS(PHIb3gb)-Y6b3*SIN(PHIb3gb))
            Y6G=Y2G+(X6b3*SIN(PHIb3gb)+Y6b3*COS(PHIb3gb))
            X7G=X2G+(X7b3*COS(PHIb3gb)-Y7b3*SIN(PHIb3gb))
            Y7G=Y2G+(X7b3*SIN(PHIb3gb)+Y7b3*COS(PHIb3gb))
C
C           BODY 4:
C           WRITE (*,184)
C184        FORMAT (10X,'got to the beginning of body 4')
            rI57=(X7G-X5G)
            rJ57=(Y7G-Y5G)
            rI54=(X4G-X5G)
            rJ54=(Y4G-Y5G)
            TEMP7554=((rI57*rI54)+(rJ57*rJ54))/(D45*D57)
C           check for assembly of body 4;
                if ((TEMP7554**2).lt.1) go to 41
                iassembly = 0
                go to 999
41          ALPHA7554=ACOS(TEMP7554)
C           check for assembly of body 4;
            if(((D45**2)+(D57**2)).gt.(2*D45*D57*COS(ALPHA7554)))go to 42
                iassembly = 0
                go to 999
42          D47=SQRT(D45**2+D57**2-(2*D45*D57*COS(ALPHA7554)))
C           check for assembly of body 4;
                if (D47.LT.(D78+D48)) go to 43
                iassembly = 0
                go to 999
43          TEMP4887=((D48**2)+(D78**2)-(D47**2))/(2*D48*D78)
C            check for assembly of body 4;
                if ((TEMP4887**2).lt.1) go to 44
                iassembly = 0
```

```
              go to 999
44       ALPHA4887=ACOS(TEMP4887)
         TEMP5447=((D45**2)+(D47**2)-(D57**2))/(2*D45*D47)
C        check for assembly of body 4;
              if ((TEMP5447**2).lt.1) go to 45
              iassembly = 0
              go to 999
45       ALPHA5447=ACOS(TEMP5447)
         TEMP7448=((D47**2)+(D48**2)-(D78**2))/(2*D47*D48)
C        check for assembly of body 4;
              if ((TEMP7448**2).lt.1) go to 46
              iassembly = 0
              go to 999
46       ALPHA7448=ACOS(TEMP7448)
         R4=D45/(D45+D57)
         rM4=ALPHA7448+ALPHA5447
         rN4=ALPHA7448-ALPHA5447
         IF(((R4*(X7G-X4G))+X4G).GE.X5G) ALPHA5448=rM4
         IF(((R4*(X7G-X4G))+X4G).LT.X5G) ALPHA5448=rN4
         X8b4=D45-(D48*COS(ALPHA5448))
         Y8b4=D48*SIN(ALPHA5448)
         rI57=(X7G-X5G)
         rJ57=(Y7G-Y5G)
         rI5G=0
         rJ5G=1
         TEMP755G=((rI57*rI5G)+(rJ57*rJ5G))/(D57*rJ5G)
C        check for assembly of body 4;
              if ((TEMP755G**2).lt.1) go to 47
              iassembly = 0
              go to 999
47       ALPHA755G=ACOS(TEMP755G)
         PHIb4gb=(PI/2)-ALPHA755G-ALPHA7554
         X8G=X5G+((X8b4*COS(PHIb4gb))-(Y8b4*SIN(PHIb4gb)))
         Y8G=Y5G+((X8b4*SIN(PHIb4gb))+(Y8b4*COS(PHIb4gb)))
         X9G=((X8G-X4G)*(D48+D89)/D48)+X4G
         Y9G=((Y8G-Y4G)*(D48+D89)/D48)+Y4G
C        BODY 5:
C        WRITE (*,185)
C185     FORMAT (10X,'got to the beginning of body 5')
         rI87=(X7G-X8G)
         rJ87=(Y7G-Y8G)
         rI89=(X9G-X8G)
         rJ89=(Y9G-Y8G)
         TEMP7889=((rI87*rI89)+(rJ87*rJ89))/(D78*D89)
C        check for assembly of body 5;
              if ((TEMP7889**2).lt.1) go to 51
              iassembly = 0
              go to 999
51       ALPHA7889=ACOS(TEMP7889)
C         check for assembly of body 5;
              if(((D78**2)+(D89**2)).gt.(2*D78*D89*COS(ALPHA7889)))go to 52
              iassembly = 0
              go to 999
52       D79=SQRT((D78**2)+(D89**2)-(2*D78*D89*COS(ALPHA7889)))
C        check for assembly of body 5;
              if (D79.lt.((D67*0.35)+D610+D910)) go to 53
              iassembly = 0
              go to 999
53       rI76=(X6G-X7G)
         rJ76=(Y6G-Y7G)
```

```
          rI79=(X9G-X7G)
          rJ79=(Y9G-Y7G)
          TEMP6779=((rI76*rI79)+(rJ76*rJ79))/(D67*D79)
C         check for assembly of body 5;
                if ((TEMP6779**2).lt.1) go to 54
                iassembly = 0
                go to 999
54        ALPHA6779=ACOS(TEMP6779)
C         check for assembly of body 5;
                if(((D67**2)+(D79**2)).gt.(2*D67*D79*COS(ALPHA6779)))go to 55
                iassembly = 0
                go to 999
55        D69=SQRT((D67**2)+(D79**2)-(2*D67*D79*COS(ALPHA6779)))
C         check for assembly of body 5;
                if (D69.lt.(D610+D910)) go to 56
                iassembly = 0
                go to 999
56        TEMP7996=((D69**2)+(D79**2)-(D67**2))/(2*D69*D79)
C         check for assembly of body 5;
                if ((TEMP7996**2).lt.1) go to 57
                iassembly = 0
                go to 999
57        ALPHA7996=ACOS(TEMP7996)
          TEMP69910=((D69**2)+(D910**2)-(D610**2))/(2*D69*D910)
C          check for assembly of body 5;
                if ((TEMP69910**2).lt.1) go to 58
                iassembly = 0
                go to 999
58        ALPHA69910=ACOS(TEMP69910)
          R5=D67/(D67+D79)
          rM5=ALPHA69910+ALPHA7996
          rN5=ALPHA69910-ALPHA7996
          IF(((R5*(X9G-X6G))+X6G).GE.X7G) ALPHA79910=rM5
          IF(((R5*(X9G-X6G))+X6G).LT.X7G) ALPHA79910=rN5
          X10b5=D79-(D910*COS(ALPHA79910))
          Y10b5=D910*(SIN(ALPHA79910))
          rI79=(X9G-X7G)
          rJ57=(Y9G-Y7G)
          rI7G=0
          rJ7G=1
          TEMP797G=((rI79*rI7G)+(rJ79*rJ7G))/(D79*rJ7G)
C          check for assembly of body 5;
                if ((TEMP797G**2).lt.1) go to 59
                iassembly = 0
                go to 999
59        ALPHA797G=ACOS(TEMP797G)
          IF(X9G.GT.X7G) PHIb5gb=(PI/2)-ALPHA797G
          IF(X9G.LT.X7G) PHIb5gb=ALPHA797G-(3*PI/2)
          X10G=X7G+((X10b5*COS(PHIb5gb))-(Y10b5*SIN(PHIb5gb)))
          Y10G=Y7G+((X10b5*SIN(PHIb5gb))+(Y10b5*COS(PHIb5gb)))
C         BODY 6:
C          WRITE (*,186)
C186      FORMAT (10X,'got to the beginning of body 6')
          U3=(D1112**2)+(D1012**2)
          U4=(2*D1012*D611)-(2*(D1012**2))-(D611**2)-(D610**2)
          U5=(2*D1012*D610)-(2*D611*D610)
          TEMP116610=((U3+U4)/U5)
C         check for assembly of body 6;
                if ((TEMP116610**2).lt.1) go to 61
                iassembly = 0
```

```
          go to 999
61        ALPHA116610=ACOS(TEMP116610)
          TEMP6111112=((D611-(D610*COS(ALPHA116610))-D1012))/D1112
C         check for assembly of body 6;
                if ((TEMP6111112**2).lt.1) go to 62
                iassembly = 0
                go to 999
62        ALPHA6111112=ACOS(TEMP6111112)
          ALPHA6101012=PI-ALPHA116610
          X11b6=D611*COS(ALPHA116610)
          Y11b6=D611*SIN(ALPHA116610)
          X12b6=D1012*COS(PI-ALPHA6101012)+D610
          Y12b6=D1012*SIN(PI-ALPHA6101012)
          PHIb6gb=ATAN((Y10G-Y6G)/(X10G-X6G))
          X11G=X6G+((X11b6*COS(PHIb6gb))-(Y11b6*SIN(PHIb6gb)))
          Y11G=Y6G+((X11b6*SIN(PHIb6gb))+(Y11b6*COS(PHIb6gb)))
          X12G=X6G+((X12b6*COS(PHIb6gb))-(Y12b6*SIN(PHIb6gb)))
          Y12G=Y6G+((X12b6*SIN(PHIb6gb))+(Y12b6*COS(PHIb6gb)))
C
C         BODY 7:
C          WRITE (*,187)
C187      FORMAT (10X,'got to the beginning of body 7')
          rI1012=(X12G-X10G)
          rJ1012=(Y12G-Y10G)
          rI109=(X9G-X10G)
          rJ109=(Y9G-Y10G)
          U6=(rI1012*rI109)+(rJ1012*rJ109)
          U7=(D910*D1012)
          U67=U6/U7
C          check for assembly of body 7;
                if ((U67**2).lt.1) go to 71
                iassembly = 0
                go to 999
71        ALPHA1210109=ACOS(U67)
          U71=(D910**2)+(D1012**2)
          U72=2*D910*D1012*COS(ALPHA1210109)
C          check for assembly of body 7;
                if (U71.gt.U72) go to 72
                iassembly = 0
                go to 999
72        D912=SQRT(U71-U72)
C         check for assembly of body 7;
                if (D912.lt.(D1213+D913)) go to 73
                iassembly = 0
                go to 999
73        U8=(D913**2)+(D1213**2)-(D912**2)
          U9=(2*D913*D1213)'
          U10=U8/U9
C         check for assembly of body 7;
                if ((U10**2).lt.1) go to 74
                iassembly = 0
                go to 999
74        ALPHA9131312=ACOS(U10)
          U11=(D910**2)+(D912**2)-(D1012**2)
          U12=(2*D910*D912)
          U13=U11/U12
C         check for assembly of body 7;
                if ((U13**2).lt.1) go to 75
                iassembly = 0
                go to 999
```

```
75          ALPHA109912=ACOS(U13)
            U14=(D912**2)+(D913**2)-(D1213**2)
            U15=(2*D912*D913)
            U16=U14/U15
C           check for assembly of body 7;
                   if ((U16**2).lt.1) go to 76
                   iassembly = 0
                   go to 999
76          ALPHA129913=ACOS(U16)
            R7=D1012/(D1012+D910)
            rM7=ALPHA129913+ALPHA109912
            rN7=ALPHA129913-ALPHA109912
            IF(((R7*(X9G-X12G))+X12G).GE.X10G) ALPHA109913=rM7
            IF(((R7*(X9G-X12G))+X12G).LT.X10G) ALPHA109913=rN7
            X13b7=D910-(D913*COS(ALPHA109913))
            Y13b7=D913*SIN(ALPHA109913)
            rI109=X9G-X10G
            rJ109=Y9G-Y10G
            rI10G=0
            rJ10G=1
            TEMP91010G=((rI109*rI10G)+(rJ109*rJ10G))/(D910*rJ10G)
                   if ((TEMP91010G**2).lt.1) go to 77
                   iassembly = 0
                   go to 999
77          ALPHA91010G=ACOS(TEMP91010G)
            IF(X9G.GE.X10G) PHIb7gb=(PI/2)-ALPHA91010G
            IF(X9G.LT.X10G) PHIb7gb=(PI/2)+ALPHA91010G
            X13G=X10G+((X13b7*COS(PHIb7gb))-(Y13b7*SIN(PHIb7gb)))
            Y13G=Y10G+((X13b7*SIN(PHIb7gb))+(Y13b7*COS(PHIb7gb)))
            X15G=(((X13G-X9G)*(D913+D1315))/D913)+X9G
            Y15G=(((Y13G-Y9G)*(D913+D1315))/D913)+Y9G
C
C           BODY 8:
C            WRITE (*,188)
C188        FORMAT (10X,'got to the beginning of body 8')
            rI1312=(X12G-X13G)
            rJ1312=(Y12G-Y13G)
            rI1315=(X15G-X13G)
            rJ1315=(Y15G-Y13G)
            U16=(rI1312*rI1315)+(rJ1312*rJ1315)
            U17=(D1213*D1315)
            U1617=U16/U17
C            check for assembly of body 8:
                   if ((U1617**2).lt.1) go to 81
                   iassembly = 0
                   go to 999
81          ALPHA12131315=ACOS(U1617)
            U18=(D1213**2)+(D1315**2)
            U19=(2*D1213*D1315*COS(ALPHA12131315))
C           check for assembly of body 8:
                   if (U18.gt.U19) go to 82
                   iassembly = 0
                   go to 999
82          D1215=SQRT(U18-U19)
            rI1211=(X11G-X12G)
            rJ1211=(Y11G-Y12G)
            rI1215=(X15G-X12G)
            rJ1215=(Y15G-Y12G)
            U20=(rI1211*rI1215)+(rJ1211*rJ1215)
            U21=(D1112*D1215)
```

```
      U2021=U20/U21
C      check for assembly of body 8;
          if ((U2021**2).lt.1) go to 83
          iassembly = 0
          go to 999
83    ALPHA11121215=ACOS(U2021)
      U22=(D1112**2)+(D1215**2)
      U23=2*D1112*D1215*COS(ALPHA11121215)
C     check for assembly of body 8;
          if (U22.gt.U23) go to 84
          iassembly = 0
          go to 999
84    D1115=SQRT(U22-U23)
C      check for assembly of body 8;
          if (D1115.LT.(D1116+D1516)) go to 85
          iassembly = 0
          go to 999
85    U24=(D1116**2)+(D1516**2)-(D1115**2)
      U25=(2*D1116*D1516)
      U2425=U24/U25
C     check for assembly of body 8;
          if ((U2425**2).lt.1) go to 86
          iassembly = 0
          go to 999
86    ALPHA11161615=ACOS(U2425)
      U26=(D1115**2)+(D1215**2)-(D1112**2)
      U27=(2*D1115*D1215)
      U2627=U26/U27
C     check for assembly of body 8;
          if ((U2627**2).lt.1) go to 87
          iassembly = 0
          go to 999
87    ALPHA12151511=ACOS(U2627)
      U28=(D1115**2)+(D1516**2)-(D1116**2)
      U29=(2*D1115*D1516)
      U2829=U28/U29
C     check for assembly of body 8;
          if ((U2829**2).lt.1) go to 88
          iassembly = 0
          go to 999
88    ALPHA11151516=ACOS(U2829)
      R8=D1112/(D1215+D1112)
      rM8=ALPHA11151516+ALPHA12151511
      rN8=ALPHA11151516-ALPHA12151511
      IF(((R8*(Y15G-Y11G))+Y11G).GE.Y12G) ALPHA12151516=rM8
      IF(((R8*(Y15G-Y11G))+Y11G).LT.Y12G) ALPHA12151516=rN8
      X16b8=D1215-(D1516*COS(ALPHA12151516))
      Y16b8=D1516*SIN(ALPHA12151516)
      rI1215=(X15G-X12G)
      rJ1215=(Y15G-Y12G)
      rI12G=0
      rJ12G=1
      U30=(rI1215*rI12G)+(rJ1215*rJ12G)
      U31=(D1215*rJ12G)
      U3031=U30/U31
C     check for assembly of body 8;
          if ((U3031**2).lt.1) go to 89
          iassembly = 0
          go to 999
89    ALPHA151212G=ACOS(U3031)
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```
      IF (X15G.GE.X12G) PHIb8gb=(PI/2)-ALPHA151212G
      IF (X15G.LT.X12G) PHIb8gb=(PI/2)+ALPHA151212G
      X16G=X12G+((X16b8*COS(PHIb8gb))-(Y16b8*SIN(PHIb8gb)))
      Y16G=Y12G+((X16b8*SIN(PHIb8gb))+(Y16b8*COS(PHIb8gb)))
C
C     BODY 9:
C      WRITE (*,189)
C189  FORMAT (10X,'got to the beginning of body 9')
      U32=(D1117**2)+(D1116**2)-(D1617**2)
      U33=(2*D1117*D1116)
      U3233=U32/U33
C     check for assembly of body 9;
            if ((U3233**2).lt.1) go to 91
            iassembly = 0
            go to 999
91    ALPHA17111116=ACOS(U3233)
      X17b9=D1117*COS(ALPHA17111116)
      Y17b9=D1117*SIN(ALPHA17111116)
      rI1116=(X16G-X11G)
      rJ1116=(Y16G-Y11G)
      rI11G=0
      rJ11G=1
      U34=(rI1116*rI11G)+(rJ1116*rJ11G)
      U35=(D1116*rJ11G)
      TEMP161111GV=(U34/U35)
C     check for assembly of body 9;
            if ((TEMP161111GV**2).lt.1) go to 92
            iassembly = 0
            go to 999
92    ALPHA161111GV=ACOS(TEMP161111GV)
      rM9=(PI/2)-ALPHA161111GV
      rN9=(PI/2)+ALPHA161111GV
      IF (X16G.GE.X11G) PHIb9gb=rM9
      IF (X16G.LT.X11G) PHIb9gb=rN9
      X17G=X11G+((X17b9*COS(PHIb9gb))-(Y17b9*SIN(PHIb9gb)))
      Y17G=Y11G+((X17b9*SIN(PHIb9gb))+(Y17b9*COS(PHIb9gb)))
C
C     If the linkage does not assemble, the program would have defaulted to 999 below:
999   CONTINUE
C
C     WRITE (*,1) CA,D1516,D1315
C1    FORMAT (3X,'CA = ',F8.4,'D1516 = ',F8.4,'D1315 = ',F8.4)
C     WRITE (*,2) D1213,D913,D910
C2    FORMAT (3X,'D1213 = ',F8.4,'D913 = ',F8.4,'D910 = ',F8.4)
C     WRITE (*,3) D89,D78,D48
C3    FORMAT (3X,'D89 = ',F8.4,'D78 = ',F8.4,'D48 = ',F8.4)
C     WRITE (*,4) D45,D34
C4    FORMAT (3X,'D45 = ',F8.4,'D34 = ',F8.4)
C     WRITE (*,5) X4G,Y4G
C5    FORMAT (3X,'X4G =',F8.3,3X,'Y4G =',F8.3)
C     WRITE (*,10) X5G,Y5G
C10   FORMAT (3X,'X5G =',F8.3,3X,'Y5G =',F8.3)
C     WRITE (*,15) X6G,Y6G
C15   FORMAT (3X,'X6G =',F8.3,3X,'Y6G =',F8.3)
C     WRITE (*,20) X7G,Y7G
C20   FORMAT (3X,'X7G =',F8.3,3X,'Y7G =',F8.3)
C     WRITE (*,251) X8G,Y8G
C251  FORMAT (3X,'X8G =',F8.3,3X,'Y8G =',F8.3)
C     WRITE (*,30) X9G,Y9G
C30   FORMAT (3X,'X9G =',F8.3,3X,'Y9G =',F8.3)
```

```
C        WRITE (*,35) X10G,Y10G
C35      FORMAT (3X,'X10G =',F7.3,3X,'Y10G =',F7.3)
C        WRITE (*,40) X11G,Y11G
C40      FORMAT (3X,'X11G =',F7.3,3X,'Y11G =',F7.3)
C        WRITE (*,451) X12G,Y12G
C451     FORMAT (3X,'X12G =',F7.3,3X,'Y12G =',F7.3)
C        WRITE (*,50) X13G,Y13G
C50      FORMAT (3X,'X13G =',F7.3,3X,'Y13G =',F7.3)
C        WRITE (*,551) X15G,Y15G
C551     FORMAT (3X,'X15G =',F7.3,3X,'Y15G =',F7.3)
C        WRITE (*,60) X16G,Y16G
C60      FORMAT (3X,'X16G =',F7.3,3X,'Y16G =',F7.3)
C        WRITE (*,651) X17G,Y17G
C651     FORMAT (3X,'X17G =',F7.3,3X,'Y17G =',F7.3)
C        if (IASSEMBLY.EQ.0) go to 67
C        if (IASSEMBLY.EQ.1) go to 69
C67      WRITE (*,68)
C68      FORMAT (3X,'Linkage does not assemble')
C        go to 711
C69      WRITE (*,70)
C70      FORMAT (3X,'Linkage does assemble')
711      CONTINUE
C
                 if (IASSEMBLY.EQ.0) rCOMP=0
                 if (IASSEMBLY.EQ.0) go to 300
C
C        CALCULATION OF FINGER JOINT ANGLES:
         rI26=(X6G-X2G)
         rj26=(Y6G-Y2G)
         rI21=(X1G-X2G)
         rJ21=(Y1G-Y2G)
         rUMCP=((rI26*rI21)+(rJ26*rJ21))
         rLMCP=(D26*D12)
         rAMCP=rUMCP/rLMCP
C        check MCP joint angle;
                 if ((rAMCP**2).lt.1) go to 205
                 rMCP=300
                 go to 210
205      ALPHAMCP=ACOS(rAMCP)
C        check that the joint is not hyper-extended:
         D16=SQRT((D12**2)+(D26**2)-(2*D12*D26*COS(ALPHAMCP)))
         A3=((D12**2)+(D16**2)-(D26**2))/(2*(D16**2))
         IF(((A3*(Y6G-Y1G))+Y1G).GT.Y2G.AND.X6G.GT.X1G) TESTMCP=1
         IF(((A3*(Y6G-Y1G))+Y1G).LT.Y2G.AND.X6G.LT.X1G) TESTMCP=1
         rMCP=180-(ALPHAMCP*(180/PI))
210      CONTINUE
C        WRITE (*,80) rMCP'
C80      FORMAT (3X,'MCP angle is',F7.3)
         rI611=(X11G-X6G)
         rJ611=(Y11G-Y6G)
         rI62=(X2G-X6G)
         rJ62=(Y2G-Y6G)
         rUPIP=((rI611*rI62)+(rJ611*rJ62))
         rLPIP=(D611*D26)
         rAPIP=rUPIP/rLPIP
C        check PIP angle;
                 if((rAPIP**2).lt.1) go to 212
                 rPIP=400
                 go to 214
212      ALPHAPIP=ACOS(rAPIP)
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C         check that the joint is not hyper-extended
          D211=SQRT((D26**2)+(D611**2)-(2*D26*D611*COS(ALPHAPIP)))
          A6=((D26**2)+(D211**2)-(D611**2))/(2*(D211**2))
          IF(((A6*(Y11G-Y2G))+Y2G).GT.Y6G.AND.X11G.GT.X2G) TESTPIP=1
          IF(((A6*(Y11G-Y2G))+Y2G).LT.Y6G.AND.X11G.LT.X2G) TESTPIP=1
          rPIP=180-(ALPHAPIP*(180/PI))
214       CONTINUE
C         WRITE (*,851) rPIP
C851      FORMAT (3X,'PIP angle is',F7.3)
          rI1117=(X17G-X11G)
          rJ1117=(Y17G-Y11G)
          rI116=(X6G-X11G)
          rJ116=(Y6G-Y11G)
          rUDIP=((rI1117*rI116)+(rJ1117*rJ116))
          rLDIP=(D611*D1117)
          rADIP=rUDIP/rLDIP
C         check DIP joint angle;
                if ((rADIP**2).lt.1) go to 215
                rDIP=300
                go to 220
215       ALPHADIP=ACOS(rADIP)
C         check that the joint is not hyper-extended:
          D617=SQRT((D611**2)+(D1117**2)-(2*D611*D1117*COS(ALPHADIP)))
          A9=((D611**2)+(D617**2)-(D1117**2))/(2*(D617**2))
          IF(((A9*(Y17G-Y6G))+Y6G).GT.Y11G.AND.X17G.GT.X6G) TESTDIP=1
          IF(((A9*(Y17G-Y6G))+Y6G).LT.Y11G.AND.X17G.LT.X6G) TESTDIP=1
          rDIP=180-(ALPHADIP*(180/PI))
220       CONTINUE
C         WRITE (*,90) rDIP
C90       FORMAT (3X,'DIP angle is',F7.3)
C
C         CHECK THAT NO JOINT IS HYPER-EXTENDED - IF SO, TRY ANOTHER CRANK
ANGLE
          IF (TESTMCP.EQ.0.OR.TESTPIP.EQ.0.OR.TESTDIP.EQ.0.) GO TO 1000
          rCOMP=rMCP+rPIP+rDIP
C
300       CONTINUE
C         WRITE (*,95) rCOMP
C95        FORMAT (3X,'The combined angle is ',F8.3)
C
C         DETERMINE IF A PART SOLUTION HAS ALREADY BEEN FOUND.
C         IF SO, AVOID LOOKING FOR ANOTHER;
                IF (TP.EQ.1) GO TO 1594
C
C         LOOK FOR A PART SOLUTION (for the mcp and pip joints only)
                IF (rMCP.LT.(TMCPf+BANDMCP).AND.rMCP.GE.TMCPf) T11p = 1
                IF (rMCP.GT.(TMCPf-BANDMCP).AND.rMCP.LE.TMCPf) T11p = 1
                IF (rPIP.LT.(TPIPf+BANDPIP).AND.rPIP.GE.TPIPf) T12p = 1
                IF (rPIP.GT.(TPIPf-BANDPIP).AND.rPIP.LE.TPIPf) T12p = 1

                IF (rMCP.LT.(TMCPm+BANDMCP).AND.rMCP.GE.TMCPm) T21p = 1
                IF (rMCP.GT.(TMCPm-BANDMCP).AND.rMCP.LE.TMCPm) T21p = 1
                IF (rPIP.LT.(TPIPm+BANDPIP).AND.rPIP.GE.TPIPm) T22p = 1
                IF (rPIP.GT.(TPIPm-BANDPIP).AND.rPIP.LE.TPIPm) T22p = 1

                IF (rMCP.LT.(TMCPe+BANDMCP).AND.rMCP.GE.TMCPe) T31p = 1
                IF (rMCP.GT.(TMCPe-BANDMCP).AND.rMCP.LE.TMCPe) T31p = 1
                IF (rPIP.LT.(TPIPe+BANDPIP).AND.rPIP.GE.TPIPe) T32p = 1
                IF (rPIP.GT.(TPIPe-BANDPIP).AND.rPIP.LE.TPIPe) T32p = 1
C
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C
C       DETERMINE IF TWO TARGETS HAVE BEEN MET IN THE CRANK CYCLE;
              IF (T11p.EQ.1.AND.T12p.EQ.1)  T1p = 1
              IF (T21p.EQ.1.AND.T22p.EQ.1)  T2p = 1
              IF (T31p.EQ.1.AND.T32p.EQ.1)  T3p = 1
C
C       write (*,1351) COUNT, CA
C1351   format (3x,' COUNT = ',I6,5X,'CRANK ANGLE =',F10.4)
C       write (*,1352) T1p,T2p,T3p
C1352   format (3x,'T1p = ',F3.0,5X,'T2p = ',F3.0,5X,'T3p = ',F3.0)
C
C       IF THEY HAVE, RECORD THE PART SOLUTION;
              IF (T1p.EQ.1.AND.T2p.EQ.1.AND.T3p.EQ.1) TP = 1
C       ... OTHERWISE CONTINUE TO LOOK FOR A FULL SOLUTION;
              IF (TP.NE.1) GO TO 1594
C       SAVE THE LINK LENGTHS OF THE PART SOLUTION;
        OPEN(UNIT=6,FILE='OPTALLp.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
        WRITE (6,1005) D1516,D1315,D1213,D913,D910,D89,D78,D48,D45,D34
        CLOSE (UNIT=6)
C
1594    CONTINUE
C
C       LOOK FOR A FULL SOLUTION (for all three joints)
              IF (rMCP.LT.(TMCPf+BANDMCP).AND.rMCP.GE.TMCPf) T11 = 1
              IF (rMCP.GT.(TMCPf-BANDMCP).AND.rMCP.LE.TMCPf) T11 = 1
              IF (rPIP.LT.(TPIPf+BANDPIP).AND.rPIP.GE.TPIPf) T12 = 1
              IF (rPIP.GT.(TPIPf-BANDPIP).AND.rPIP.LE.TPIPf) T12 = 1
              IF (rDIP.LT.(TDIPf+BANDDIP).AND.rDIP.GE.TDIPf) T13 = 1
              IF (rDIP.GT.(TDIPf-BANDDIP).AND.rDIP.LE.TDIPf) T13 = 1

              IF (rMCP.LT.(TMCPm+BANDMCP).AND.rMCP.GE.TMCPm) T21 = 1
              IF (rMCP.GT.(TMCPm-BANDMCP).AND.rMCP.LE.TMCPm) T21 = 1
              IF (rPIP.LT.(TPIPm+BANDPIP).AND.rPIP.GE.TPIPm) T22 = 1
              IF (rPIP.GT.(TPIPm-BANDPIP).AND.rPIP.LE.TPIPm) T22 = 1
              IF (rDIP.LT.(TDIPm+BANDDIP).AND.rDIP.GE.TDIPm) T23 = 1
              IF (rDIP.GT.(TDIPm-BANDDIP).AND.rDIP.LE.TDIPm) T23 = 1

              IF (rMCP.LT.(TMCPe+BANDMCP).AND.rMCP.GE.TMCPe) T31 = 1
              IF (rMCP.GT.(TMCPe-BANDMCP).AND.rMCP.LE.TMCPe) T31 = 1
              IF (rPIP.LT.(TPIPe+BANDPIP).AND.rPIP.GE.TPIPe) T32 = 1
              IF (rPIP.GT.(TPIPe-BANDPIP).AND.rPIP.LE.TPIPe) T32 = 1
              IF (rDIP.LT.(TDIPe+BANDDIP).AND.rDIP.GE.TDIPe) T33 = 1
              IF (rDIP.GT.(TDIPe-BANDDIP).AND.rDIP.LE.TDIPe) T33 = 1
C
C       WRITE (*,2091) CA,rMCP,TMCPf,T11,T21,T31
C2091   FORMAT (3X,F10.5,2F12.5,5X,F3.1,5X,F3.1,5X,F3.1)
C       WRITE (*,2092) rPIP,TPIPf,T12,T22,T32
C2092   FORMAT (13X,2F12.5,5X,F3.1,5X,F3.1,5X,F3.1)
C       WRITE (*,2093) rDIP,TDIPf,T13,T23,T33
C2093   FORMAT (13X,2F12.5,5X,F3.1,5X,F3.1,5X,F3.1)
C
C       DETERMINE IF ALL THREE TARGETS HAVE BEEN MET IN THE CRANK CYCLE;
              IF (T11.EQ.1.AND.T12.EQ.1.AND.T13.EQ.1)  T1 = 1
              IF (T21.EQ.1.AND.T22.EQ.1.AND.T23.EQ.1)  T2 = 1
              IF (T31.EQ.1.AND.T32.EQ.1.AND.T33.EQ.1)  T3 = 1
C
C       WRITE (*,532) T1,T2,T3
C
C       IF THEY HAVE, TERMINATE PROGRAM;
              IF (T1.EQ.1.AND.T2.EQ.1.AND.T3.EQ.1) TF = 1
```

```
               IF (T1.EQ.1.AND.T2.EQ.1.AND.T3.EQ.1) GO TO 99999
C
C        OTHERWISE, REPEAT FOR ANOTHER CRANK ANGLE;
1000     CONTINUE
C
         COUNT = COUNT + 1
C532     FORMAT (3X,'T1 =',F3.0,5X,'T2 = ',F3.0,5X,'T3 =',F3.0)
C        WRITE (*,531)
C        PRINT 'COUNT' TO SCREEN EVERY 500,000 CYCLES OF THE CRANK:
                   IF (COUNT.LT.(500000*TEST)) GO TO 887
                   TEST=TEST+1
                   PERCENT = COUNT*100/rNCC
                   WRITE (*,885) COUNT,rNCC,PERCENT
885      FORMAT (3X,I20,' /',F15.0,3X,F7.2)
C        WRITE (*,531)
C        WRITE (*,531)
C531     FORMAT (3X,' ')
887      CONTINUE
C
C
2000     CONTINUE
3000     CONTINUE
4000     CONTINUE
5000     CONTINUE
6000     CONTINUE
7000     CONTINUE
8000     CONTINUE
9000     CONTINUE
10000    CONTINUE
11000    CONTINUE
         IF (TF.EQ.0) GO TO 1007
C
99999    OPEN(UNIT=6,FILE='OPTALLf.DAT',STATUS='NEW',ACCESS='SEQUENTIAL')
         WRITE (6,1005) D1516,D1315,D1213,D913,D910,D89,D78,D48,D45,D34
1005     FORMAT (1X,10F9.2)
1006     CLOSE (UNIT=6)
C
1007     STOP
         END
```

Appendix 4

Statistical analysis of the recovery of hand function following surgery and conventional treatment methods

NON-OPERATED HAND *spss1.xls*

patient		hand dom	op hand	sex	occup	age	tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
1	TG	R	L	M	MW	65	4.95	9.13	5.64	6.04	5.13	9.00	6.46	0	0	0	0	0	0	0	0	0	65	75	15
2	DS	R	R	M	MW	68	4.74	7.97	3.69	5.13	2.28	2.11	4.35	0	0	0	0	0	0	0	0	0	0	0	0
3	JI	L	R	M	MW	60	4.30	6.97	5.95	6.31	6.72	6.25	3.87	0	5	0	0	0	0	0	0	0	20	60	0
4	RB	R	L	M	LW	54	5.22	8.57	7.02	5.04	2.96	4.79	8.93	0	0	0	0	0	0	0	0	0	0	0	0
5	JD	-1	R	M	OW	86	2.51	3.65	2.39	2.21	1.56	2.07	2.47	0	0	0	0	0	0	0	0	0	0	55	10
6	DM	-1	R	M	MW	59	4.03	6.50	3.34	3.92	3.43	1.08	3.70	0	0	0	0	0	0	0	10	0	0	0	0
7	EF	R	R	M	OW	61	5.71	9.50	5.39	5.51	5.20	4.47	8.36	0	0	0	0	0	0	0	0	0	0	0	0
8	JL	R	R	M	MW	76	4.94	8.19	2.88	0.59	1.62	1.78	9.26	0	0	0	0	25	0	0	0	0	0	0	0
9	SM	-1	L	F	SW	66	2.58	2.84	4.15	3.84	3.02	2.78	1.64	0	5	0	0	0	0	0	0	0	0	0	0
10	AH	L	L	M	MW	68	2.51	5.12	4.28	1.74	1.47	1.62	6.96	0	5	0	0	10	25	0	0	0	20	45	0
11	JW	R	R	M	OW	77	6.20	8.22	4.00	4.54	2.91	2.85	5.38	0	0	0	0	0	0	0	0	0	0	0	0
12	AC	R	L	M	MW	68	4.44	9.43	3.25	2.81	2.79	4.83	2.99	0	0	0	25	0	0	40	10	0	50	75	0
13	SH	R	R	M	MW	58	5.95	11.89	6.21	6.18	5.18	5.15	7.10	0	0	0	0	0	0	0	0	0	0	0	0
14	RS	R	L	M	OW	62	7.29	11.00	4.76	6.05	7.67	6.32	-1.00	10	20	0	0	0	0	25	45	-5	15	25	0
15	EM	R	R	M	LW	38	5.60	7.32	4.93	3.53	2.84	2.50	4.98	0	0	0	0	0	0	0	0	0	0	0	0
16	TH	-1	R	M	-1	77	5.65	5.89	4.26	8.38	6.21	4.04	3.31	0	0	0	0	0	0	0	0	0	0	0	0
17	AS	-1	R	M	-1	70	3.08	8.36	3.58	3.77	1.61	4.51	5.09	0	0	0	0	0	0	0	0	0	0	45	0
18	JH	R	L	M	LW	64	4.01	5.01	2.34	3.52	3.00	1.27	5.08	0	0	0	0	0	0	0	0	0	0	5	0
19	JL	R	L	M	OW	49	5.19	10.23	6.84	4.10	3.89	4.91	4.26	0	0	0	0	0	0	0	0	0	0	35	0
20	RM	R	R	M	MW	51	7.52	7.94	7.83	9.19	7.26	5.66	7.35	0	0	0	0	0	0	0	0	0	0	0	0
21	HO	R	L	M	LW	68	7.59	9.85	7.04	8.98	7.54	3.62	3.78	0	0	0	0	0	0	10	0	0	0	5	5
22	JC	R	R	M	MW	62	6.24	8.85	4.54	5.06	3.74	3.57	3.37	0	0	0	0	0	0	0	0	0	0	0	0
23	WM	R	R	M	OW	48	7.83	8.51	5.62	6.53	4.73	4.03	9.10	0	0	0	0	0	0	0	0	0	0	0	0
24	JA	R	R	M	MW	73	6.09	7.05	2.87	3.44	-1.00	3.70	7.10	20	0	0	50	70	0	65	85	25	60	55	0
25	NF	R	B	M	LW	67	5.79	6.44	5.15	6.68	3.18	3.73	7.14	0	20	0	0	15	5	25	15	0	5	65	0
26	ED	R	R	M	LW	44	6.70	12.98	7.45	6.62	5.73	6.64	6.88	0	0	0	0	0	0	0	0	0	0	0	0
27	GL	R	R	M	MW	67	5.52	7.32	2.69	2.25	2.24	2.37	3.52	0	0	0	0	0	0	0	0	0	0	0	0
28	DH	-1	R	M	-1	69	5.00	9.70	3.68	6.33	4.34	4.55	4.22	0	0	0	0	0	0	0	0	0	0	0	0
29	NM	R	R	M	MW	76	5.86	6.42	3.85	4.24	5.01	4.00	3.83	0	0	0	0	65	0	0	0	0	0	45	50
30	JW	R	R	M	LW	71	5.21	4.59	4.31	4.90	6.10	9.67	7.75	0	0	0	0	0	0	0	0	0	0	0	0

table A4 - 1 hand assessment results for non-operated hands

NON-OPERATED HAND

patient		hand dom	op hand	sex	occup	age	tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
31	WC	R	B	M	MW	62	5.42	7.48	3.54	3.40	3.04	2.29	6.61	15	0	0	25	0	0	25	0	0	55	0	0
32	AC	R	L	M	LW	47	8.44	10.12	7.57	11.04	8.99	6.12	5.19	0	0	0	0	0	0	0	0	0	0	0	0
33	PG	R	L	M	OW	58	4.89	6.06	4.27	5.05	3.84	3.58	8.71	0	0	0	0	0	0	0	0	0	0	0	0
34	JS	R	R	M	LW	66	4.29	8.25	1.62	1.79	1.90	2.16	6.58	0	0	0	0	0	0	20	0	0	0	0	0
35	GF	R	L	M	LW	60	5.08	6.62	2.54	1.78	1.75	1.53	7.18	0	10	0	35	15	0	20	0	0	0	35	0
36	OR	R	L	M	MW	83	6.03	7.73	2.67	5.21	2.99	-1.00	5.41	0	0	0	0	0	0	0	85	0	-1	-1	-1
37	CA	R	R	M	OF	46	5.43	9.48	4.42	4.32	3.10	2.29	4.15	0	0	0	0	0	0	0	0	0	0	0	0
38	JT	R	L	F	LW	69	4.38	6.45	2.74	2.89	2.58	1.65	6.60	0	0	0	0	0	0	0	0	0	0	0	0
39	JB	R	R	M	MW	56	5.34	9.16	5.22	3.82	2.69	3.16	5.63	0	0	0	0	0	0	0	10	0	0	30	0
40	DW	R	R	F	LW	68	3.30	4.11	1.40	1.31	0.97	0.85	0.77	0	5	0	35	0	0	30	0	0	0	5	0
41	DH	L	R	M	OW	72	6.13	9.15	5.38	5.23	4.20	3.89	9.38	0	5	0	0	0	0	0	0	0	0	0	0
42	DM	R	L	M	LW	58	3.50	5.40	6.01	5.07	4.33	3.60	6.47	0	0	0	0	10	0	5	0	0	10	15	0
43	DR	R	R	M	LW	69	5.80	5.34	1.81	2.17	2.13	1.91	3.12	0	0	0	0	0	0	0	5	0	0	15	0
44	RG	R	R	M	MW	72	5.97	7.23	3.98	6.03	7.53	4.65	1.75	0	0	0	0	0	0	0	0	0	0	5	0
45	ST	R	L	M	MW	56	3.91	6.96	3.74	2.81	1.85	2.45	3.66	0	0	0	0	0	0	35	5	5	0	5	0
46	CS	R	R	M	MW	64	5.42	6.86	1.76	3.23	3.48	2.53	3.79	0	0	0	0	0	0	0	15	0	0	10	0
47	RP	R	L	M	MW	60	4.90	5.88	3.81	3.17	2.20	0.34	5.13	0	0	0	0	0	0	0	5	0	0	0	0
48	RB	L	L	M	MW	58	3.65	7.16	4.86	5.67	4.50	4.92	6.45	0	0	0	0	0	0	0	0	0	0	0	0
min:							2.51	2.84	1.40	0.59	0.97	0.34	0.77	0	0	0	0	0	0	0	0	-5	0	0	0
max:							8.44	12.98	7.83	11.04	8.99	9.67	9.38	20	20	0	50	70	25	65	85	25	65	75	50
range:							5.93	10.14	6.43	10.45	8.02	9.33	8.61	20	20	0	50	70	25	65	85	30	65	75	50
mean:							5.21	7.60	4.14	4.61	3.86	3.53	5.42	0.94	1.46	0.00	3.54	4.38	0.63	6.25	6.04	0.52	6.38	15.11	1.92
standard error:							0.20	0.30	0.24	0.31	0.28	0.26	0.31	0.55	0.63	0.00	1.58	2.05	0.53	1.98	2.63	0.54	2.41	3.41	1.13
standard deviation:							1.35	2.08	1.65	2.14	1.94	1.80	2.15	3.81	4.37	0.00	10.91	14.20	3.67	13.74	18.19	3.75	16.54	23.37	7.77
skewness:							0.04	0.12	0.34	0.69	0.82	0.87	0.03	4.18	3.57	0.00	3.08	3.98	6.57	2.52	3.83	6.13	2.76	1.38	5.53
kurtosis:							0.14	0.22	-0.49	0.83	-0.04	1.56	-0.68	17.18	12.86	0.00	8.81	15.97	44.16	6.77	14.49	40.72	6.53	0.55	33.37

table A4 - 1 hand assessment results for non-operated hands

OPERATED HAND: PRE-SURGERY *spss2.xls*

patient		tip	lateral	index	middle	ring	little	skin	index			middle			ring			little		
		pinch	pinch	grasp	grasp	grasp	grasp	shear	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
1	TG	3.81	9.63	3.24	3.50	3.95	3.68	3.87	0	0	0	0	0	0	0	0	0	65	45	25
2	DS	5.25	7.88	5.94	6.26	4.50	2.73	3.56	0	0	0	0	0	0	35	55	0	0	0	0
3	JI	5.22	9.05	5.15	6.37	5.84	4.92	5.07	0	0	0	0	50	10	0	65	20	55	85	25
4	RB	4.91	7.53	8.07	5.42	6.02	6.56	9.20	0	0	0	0	0	0	0	0	0	75	55	0
5	JD	3.92	7.13	4.34	3.20	2.79	2.32	4.01	0	0	0	0	0	0	65	5	0	65	40	5
6	DM	4.28	6.93	5.60	4.15	2.29	1.84	2.20	0	0	0	0	0	0	0	0	0	45	25	5
7	EF	5.44	9.82	8.68	5.39	3.90	2.38	10.17	0	0	0	0	0	0	0	0	0	10	0	0
8	JL	6.80	8.01	2.95	2.81	1.03	1.92	7.14	0	0	0	35	0	0	35	50	0	0	0	0
9	SM	2.77	4.94	3.26	2.44	1.98	1.01	3.69	0	0	0	0	0	0	0	0	0	40	40	0
10	AH	1.40	4.55	1.59	1.58	1.23	2.12	4.44	0	0	0	30	10	0	0	0	0	-1	-1	-1
11	JW	5.92	9.22	4.08	3.10	3.67	2.61	4.57	0	0	0	0	0	0	60	90	0	0	0	0
12	AC	5.94	7.76	3.91	3.63	3.94	3.68	5.05	0	0	0	30	75	0	45	50	0	30	75	0
13	SH	6.94	12.24	6.06	8.42	4.06	5.46	6.44	0	0	0	0	0	0	0	0	0	0	0	0
14	RS	6.33	9.19	6.43	7.72	7.06	-1.00	5.71	0	0	0	0	0	0	30	20	0	70	70	0
15	EM	3.34	9.14	5.10	2.86	2.69	2.76	3.62	0	0	0	0	0	0	0	0	0	8	0	0
16	TH	5.48	5.75	2.66	4.36	3.75	3.40	4.31	0	0	0	0	0	0	0	0	0	10	5	0
17	AS	2.67	10.22	3.27	2.67	1.62	3.08	8.52	0	0	0	0	0	0	0	10	0	40	60	0
18	JH	3.81	6.42	3.36	3.51	1.82	1.40	4.56	0	0	0	0	0	0	0	0	0	0	20	0
19	JL	6.11	7.74	5.87	4.72	4.27	3.81	4.02	0	0	0	30	0	0	50	0	0	15	0	0
20	RM	8.90	8.58	8.33	9.41	-1.00	4.65	6.56	0	0	0	55	0	0	5	65	5	0	0	0
21	HO	8.30	9.10	5.26	6.28	5.13	2.68	4.67	0	35	0	0	50	0	5	65	25	0	10	0
22	JC	6.45	9.88	5.80	7.79	2.98	3.06	5.81	0	5	0	0	15	0	30	65	0	0	10	0
23	WM	4.53	9.01	6.05	5.74	6.10	4.28	9.06	10	0	0	35	0	0	60	45	0	0	0	0
24	JA	4.71	5.70	5.56	5.81	-1.00	-1.00	3.80	15	40	0	15	20	10	15	75	45	20	75	60

table A4 - 2 hand assessment results for operated hands

OPERATED HAND: PRE-SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
25	NF	8.31	9.32	5.27	4.91	4.58	4.06	7.11	0	20	0	25	20	0	40	10	0	60	40	10
26	ED	8.74	13.03	6.06	4.16	5.49	8.12	5.73	0	10	5	0	35	0	0	40	0	0	45	0
27	GL	6.00	7.57	4.33	5.23	4.18	3.49	4.10	0	0	0	0	0	0	25	20	5	0	0	0
28	DH	4.71	10.52	7.29	5.04	4.99	4.37	4.96	0	0	0	0	0	0	0	0	0	0	40	20
29	NM	4.02	4.75	2.60	4.44	4.39	2.55	3.31	0	0	0	0	0	0	45	70	0	10	0	0
30	JW	6.25	5.53	5.79	4.57	7.17	8.91	8.28	15	0	0	25	0	0	48	25	0	10	10	0
31	WC	6.07	8.39	9.29	5.40	2.39	4.03	6.72	0	0	0	0	0	0	25	5	0	70	5	0
32	AC	7.29	8.20	8.12	7.01	7.35	4.96	6.26	0	0	0	0	0	0	0	0	0	0	0	0
33	PG	6.01	7.02	4.67	4.81	3.06	2.09	8.90	0	0	0	0	0	0	0	0	0	0	40	0
34	JS	5.02	7.28	2.33	2.54	2.75	-1.00	5.85	0	0	0	0	0	0	10	40	0	65	80	0
35	GF	4.96	6.87	-1.00	-1.00	-1.00	-1.00	10.33	0	15	0	20	0	0	77	75	0	0	20	0
36	OR	6.50	8.53	2.48	2.71	-1.00	-1.00	5.22	0	55	0	0	5	5	0	110	10	70	105	0
37	CA	5.06	9.16	6.23	6.33	3.38	2.65	6.45	0	0	0	0	0	0	0	0	0	0	0	0
38	JT	3.73	5.88	2.51	2.11	1.57	1.43	3.31	0	0	0	0	0	0	0	0	0	55	5	0
39	JB	4.25	10.56	3.35	1.14	2.38	2.29	6.04	0	0	0	-20	20	-5	0	20	0	0	50	0
40	DW	3.67	5.08	1.39	1.54	1.24	1.21	1.94	0	0	0	35	10	0	80	0	0	85	35	-5
41	DH	5.17	9.06	2.40	4.15	4.29	-1.00	10.94	0	0	0	15	10	0	70	0	0	95	75	0
42	DM	2.88	6.44	3.56	4.27	2.87	2.27	5.19	0	5	0	0	15	0	15	15	0	10	35	0
43	DR	4.66	4.75	2.71	2.60	1.71	2.38	1.79	0	0	0	15	0	0	45	0	0	20	0	0
44	RG	4.68	6.55	6.02	4.91	5.73	3.29	1.96	20	0	0	25	0	0	35	0	0	5	0	0
45	ST	4.57	5.53	2.34	3.71	2.72	2.32	4.93	0	0	0	35	0	0	0	0	0	0	10	0
46	CS	5.70	8.34	4.58	3.33	2.87	2.11	4.43	0	0	0	30	0	40	35	15	0	40	15	0
47	RP	3.45	5.33	1.55	1.54	-1.00	-1.00	6.34	25	0	0	25	20	0	40	75	0	50	0	0
48	RB	4.29	7.49	5.44	4.33	5.67	5.76	5.28	0	0	0	0	0	0	0	0	0	0	0	0

table A4 - 2 hand assessment results for operated hands

WEEKS 2 - 4 POST SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
1	TG	3.77	4.91	2.08	1.95	1.87	2.24	3.88	0	0	0	0	0	0	0	0	0	10	10	0
2	DS	2.58	4.46	1.44	0.82	0.77	1.08	0.69	0	0	0	0	0	0	0	25	0	0	0	0
3	JI	1.42	2.36	0.93	0.55	0.53	0.67	0.09	0	0	0	0	0	0	0	20	0	0	25	0
4	RB	4.36	7.07	3.91	3.66	3.19	2.91	4.28	0	0	0	0	0	0	0	0	0	20	10	5
5	JD	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	DM	2.70	4.92	2.00	0.82	0.78	1.19	1.74	0	0	0	0	0	0	0	0	0	0	15	0
7	EF	5.58	10.03	5.15	5.25	3.02	1.97	5.99	0	0	0	0	0	0	0	0	0	0	0	0
8	JL	4.09	7.63	2.58	2.60	2.82	7.87	5.04	55	0	0	50	0	0	45	0	0	30	0	0
9	SM	2.66	4.76	2.08	2.34	2.72	2.19	4.37	0	0	0	0	0	0	0	0	0	15	0	0
10	AH	2.40	2.40	2.00	2.00	1.80	1.80	0.34	0	0	0	0	20	10	0	20	10	0	20	10
11	JW	3.93	7.42	4.17	1.92	0.98	1.24	2.82	0	0	0	0	0	0	0	25	0	0	0	0
12	AC	5.16	4.92	2.22	2.24	2.24	2.24	1.11	0	0	0	5	25	0	10	45	0	10	60	0
13	SH	6.52	8.65	4.19	4.59	4.00	2.13	3.27	0	0	0	0	0	0	0	0	0	0	0	0
14	RS	3.00	3.12	2.00	1.95	1.95	-1.00	-1.00	0	0	0	0	0	0	5	20	0	5	25	0
15	EM	2.96	5.10	2.18	2.11	2.09	1.91	1.42	0	0	0	0	0	0	0	0	0	0	0	0
16	TH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
17	AS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
18	JH	1.75	4.50	2.02	2.40	1.23	1.10	2.83	0	0	0	0	0	0	0	0	0	0	5	0
19	JL	3.44	4.63	2.94	2.22	2.04	1.91	2.41	0	0	0	0	0	0	0	0	0	0	0	0
20	RM	3.62	4.87	3.35	1.31	0.65	0.86	-1.00	0	0	0	0	0	0	10	20	0	0	0	0
21	HO	4.77	5.55	3.65	2.17	1.12	0.93	1.49	0	25	0	0	35	0	0	30	0	0	0	0
22	JC	4.98	2.10	1.48	1.83	1.33	1.35	2.36	0	0	0	0	0	0	0	25	0	0	5	0
23	WM	2.40	4.61	2.49	2.12	1.92	1.86	2.68	0	0	0	0	0	0	0	0	0	0	0	0
24	JA	4.77	4.46	3.88	2.68	2.93	1.98	2.75	0	50	5	0	35	20	10	40	35	0	55	45

table A4 - 2 hand assessment results for operated hands

WEEKS 2 - 4 POST SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
25	NF	2.98	5.40	2.65	2.54	3.14	-1.00	5.78	0	0	0	0	15	0	0	10	0	0	20	0
26	ED	8.07	10.08	8.76	6.65	5.66	6.09	3.74	0	0	0	5	0	0	5	0	0	0	0	0
27	GL	4.43	6.95	4.12	2.50	2.75	2.43	1.60	0	0	0	0	0	0	0	0	0	0	0	0
28	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
29	NM	1.70	1.39	1.66	1.38	-1.00	-1.00	-1.00	0	0	0	0	0	0	0	15	0	0	35	0
30	JW	5.01	6.80	2.91	1.83	1.48	1.90	1.95	0	0	0	0	0	0	10	15	0	0	0	0
31	WC	6.63	8.84	4.84	4.98	2.84	1.68	5.03	0	0	0	0	0	0	0	0	0	5	0	0
32	AC	8.12	8.89	5.96	4.16	4.68	4.53	3.39	0	0	0	0	0	0	0	0	0	0	0	0
33	PG	9.87	4.08	1.90	4.96	3.40	2.00	3.00	0	0	0	0	0	0	0	0	0	0	0	0
34	JS	4.91	6.40	4.59	2.35	1.56	0.92	6.19	0	0	0	0	0	0	0	25	0	0	30	0
35	GF	3.55	4.60	2.11	0.67	0.74	-1.00	2.32	25	10	0	0	0	0	20	55	0	25	35	0
36	OR	3.35	4.14	1.46	1.81	1.00	0.15	1.39	0	50	0	0	0	0	0	45	0	10	15	0
37	CA	4.40	5.29	4.27	1.97	2.39	1.50	4.45	0	0	0	0	0	0	0	0	0	0	0	0
38	JT	2.88	4.42	1.90	1.28	1.04	0.67	3.06	0	0	0	0	0	0	0	0	0	0	0	0
39	JB	4.69	8.47	3.23	1.01	1.21	0.88	3.23	0	0	0	0	10	-5	0	20	0	0	15	0
40	DW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
41	DH	3.53	6.97	4.00	2.99	1.40	0.67	3.19	0	0	0	0	0	0	10	5	0	10	10	0
42	DM	2.79	4.20	3.03	2.99	0.76	1.65	0.62	0	0	0	0	10	0	0	15	0	10	60	20
43	DR	7.31	8.37	4.06	2.66	2.70	2.12	3.15	20	0	0	30	0	0	25	0	0	25	0	0
44	RG	4.43	5.49	4.09	2.25	2.49	1.84	1.21	0	0	0	0	0	0	0	0	0	0	0	0
45	ST	2.03	5.44	1.86	2.65	3.13	3.10	2.47	0	0	0	0	0	0	0	0	0	0	0	0
46	CS	3.37	7.31	3.43	4.07	2.65	2.07	2.45	0	0	0	0	0	40	0	0	0	0	0	0
47	RP	3.26	5.06	3.18	1.53	0.63	1.51	2.55	0	0	0	15	10	0	25	35	0	20	5	0
48	RB	1.33	1.86	1.32	1.06	0.86	1.58	2.66	0	0	0	0	0	0	0	0	0	0	0	0

table A4 - 2 hand assessment results for operated hands

WEEKS 4 -6 POST SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
1	TG	4.29	5.88	3.21	2.26	2.32	2.36	3.40	0	0	0	0	0	0	0	0	0	0	0	0
2	DS	3.62	6.26	4.20	3.03	2.54	2.39	2.47	0	0	0	0	0	0	0	25	0	0	20	0
3	JI	3.31	5.96	2.95	2.28	2.87	2.99	3.52	0	0	0	0	0	0	-1	20	0	0	20	0
4	RB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5	JD	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	DM	3.45	4.93	2.48	2.08	2.02	1.95	1.06	0	0	0	0	0	0	0	0	0	5	20	0
7	EF	10.34	5.88	3.17	3.07	2.87	2.41	4.99	0	0	0	0	0	0	0	0	0	0	0	0
8	JL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
9	SM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
10	AH	2.07	3.07	1.65	1.50	1.27	1.41	2.63	0	15	0	10	25	5	0	25	0	0	25	0
11	JW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
12	AC	2.80	4.95	2.04	3.44	2.91	2.91	0.58	0	0	0	0	20	0	0	35	0	0	45	0
13	SH	5.42	9.35	5.01	4.18	3.24	2.45	3.22	0	0	0	0	0	0	0	0	0	0	10	0
14	RS	3.54	4.70	2.27	2.13	1.23	1.16	2.20	0	0	0	0	0	0	0	20	0	15	30	0
15	EM	4.07	7.64	5.07	3.39	2.17	2.24	5.20	0	0	0	0	0	0	0	0	0	0	0	0
16	TH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
17	AS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
18	JH	2.61	5.53	2.07	3.01	1.39	1.29	2.24	0	0	0	0	0	0	0	0	0	0	5	0
19	JL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
20	RM	4.90	6.60	4.03	2.98	2.18	2.00	3.68	0	0	0	0	0	0	10	35	0	0	10	0
21	HO	5.27	7.94	5.49	4.52	3.85	3.08	2.09	0	20	0	0	40	0	0	35	0	0	0	0
22	JC	3.10	6.81	2.88	2.24	1.24	1.80	3.01	0	0	0	0	0	0	0	40	0	0	5	0
23	WM	3.82	8.23	1.25	1.51	1.25	0.65	3.71	0	0	0	0	0	0	0	0	0	0	0	0
24	JA	5.49	6.38	3.28	2.05	3.15	2.47	2.59	0	45	0	0	25	20	0	40	25	0	55	0

table A4 - 2 hand assessment results for operated hands

WEEKS 4 -6 POST SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	PIP	DIP	middle MCP	PIP	DIP	ring MCP	PIP	DIP	little MCP	PIP	DIP
25	NF	4.38	6.47	3.03	4.58	3.44	2.47	10.21	0	0	0	0	15	0	0	10	0	0	30	0
26	ED	3.13	8.38	3.11	2.66	1.07	1.24	3.60	0	0	0	0	0	0	5	0	0	0	5	0
27	GL	5.62	6.82	4.69	4.50	4.28	2.50	4.26	0	0	0	0	0	0	0	0	0	0	0	0
28	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
29	NM	2.34	2.57	1.28	1.52	2.18	0.98	0.65	0	0	0	0	0	0	0	40	0	0	20	0
30	JW	4.12	6.43	2.77	1.70	1.37	1.99	2.58	0	0	0	0	0	0	5	25	0	0	0	0
31	WC	4.65	8.83	4.52	3.57	1.88	0.88	4.04	0	0	0	0	0	0	0	0	0	10	0	0
32	AC	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
33	PG	4.08	5.86	3.49	4.54	3.85	2.98	6.83	0	25	5	0	0	0	0	0	0	0	0	0
34	JS	5.88	7.23	3.79	2.75	3.07	1.57	2.53	0	0	0	0	0	0	0	30	0	0	40	0
35	GF	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
36	OR	3.96	5.74	1.86	1.50	1.60	-1.00	3.40	0	50	0	0	10	0	0	55	0	10	25	0
37	CA	3.51	6.39	4.05	3.45	9.29	2.03	5.16	0	0	0	0	0	0	0	0	0	0	0	0
38	JT	3.20	4.45	2.33	3.07	1.80	1.12	3.49	0	0	0	0	0	0	0	0	0	0	10	0
39	JB	4.43	9.32	4.86	3.23	3.94	1.83	3.82	0	0	0	0	25	0	0	20	0	0	20	0
40	DW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
41	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
42	DM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
43	DR	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
44	RG	4.76	5.84	4.32	4.74	4.24	2.49	3.02	0	0	0	0	0	0	0	0	0	0	0	0
45	ST	2.35	6.32	3.59	7.40	4.79	3.44	6.72	0	0	0	0	0	0	0	0	0	0	0	0
46	CS	5.20	6.78	3.01	4.55	3.33	2.69	7.02	0	0	0	0	0	40	0	0	0	0	5	0
47	RP	2.93	5.09	3.56	1.71	1.60	2.07	2.85	0	0	0	15	15	0	25	35	0	20	5	0
48	RB	9.54	6.65	4.7	4.74	1.51	2.73	7.13	0	0	0	0	0	0	0	0	0	0	0	0

table A4 - 2 hand assessment results for operated hands

WEEKS 6 - 8 POST SURGERY

patient		tip pinch	lateral pinch	index grasp	middle grasp	ring grasp	little grasp	skin shear	index MCP	index PIP	index DIP	middle MCP	middle PIP	middle DIP	ring MCP	ring PIP	ring DIP	little MCP	little PIP	little DIP
1	TG	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	DS	5.20	8.01	5.73	4.32	4.14	3.80	4.33	0	0	0	0	0	0	0	30	0	0	30	0
3	JI	3.46	7.11	4.58	2.56	4.29	3.76	4.55	0	0	0	0	0	0	0	20	0	0	15	0
4	RB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5	JD	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	DM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
7	EF	4.26	7.83	4.45	3.77	2.36	3.21	5.69	0	0	0	0	0	0	0	0	0	0	0	0
8	JL	6.84	9.46	3.42	2.22	2.65	2.55	6.12	0	0	0	10	0	0	10	0	0	0	0	0
9	SM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
10	AH	2.83	5.59	2.76	2.17	1.49	2.32	2.87	0	15	0	0	25	0	0	25	5	0	25	5
11	JW	4.37	7.96	3.40	2.47	2.00	1.17	4.49	10	10	0	25	10	0	25	40	0	20	5	0
12	AC	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
13	SH	5.66	7.65	3.61	4.10	4.58	2.16	6.32	0	0	0	0	0	0	0	0	0	0	10	0
14	RS	3.65	4.98	1.47	2.01	1.12	1.14	3.42	0	0	0	0	0	0	0	20	0	5	25	0
15	EM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
16	TH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
17	AS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
18	JH	2.58	5.82	1.83	2.78	1.71	1.38	3.29	0	0	0	0	0	0	0	0	0	0	5	0
19	JL	4.77	7.58	3.23	3.50	2.70	1.83	5.48	0	0	0	0	0	0	0	0	0	0	0	0
20	RM	4.53	6.01	5.83	4.02	2.02	2.07	2.24	0	0	0	35	0	0	35	20	0	20	0	0
21	HO	4.24	7.95	4.43	4.03	3.81	2.03	4.82	0	30	0	0	40	0	0	35	0	0	0	0
22	JC	5.50	2.02	2.01	1.80	2.11	1.29	0.79	0	15	0	0	20	0	0	45	0	0	20	0
23	WM	5.18	7.70	3.25	3.09	3.09	1.67	7.53	0	0	0	0	0	0	0	0	0	0	0	0
24	JA	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

table A4 - 2 hand assessment results for operated hands

WEEKS 6 - 8 POST SURGERY

patient		tip	lateral	index	middle	ring	little	skin	index			middle			ring			little		
		pinch	pinch	grasp	grasp	grasp	grasp	shear	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
25	NF	3.47	6.65	3.33	4.27	3.40	2.05	6.26	0	0	0	0	5	0	0	5	0	0	25	0
26	ED	8.01	10.94	5.69	5.76	5.78	6.11	4.78	0	0	0	0	0	0	0	0	0	0	10	0
27	GL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
28	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
29	NM	2.35	4.12	2.48	2.2	1.81	1.38	1.3	0	0	0	0	0	0	0	0	25	0	0	10
30	JW	3.91	6.03	2.81	2.35	2.01	1.65	2.75	0	0	0	0	0	0	10	30	0	0	0	0
31	WC	6.19	8.51	5.64	6.72	4.03	2.77	6.19	0	0	0	0	0	0	0	0	0	0	0	0
32	AC	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
33	PG	3.75	6.17	3.59	5.97	3.67	3.16	5.53	0	35	0	0	0	0	0	0	0	0	0	0
34	JS	5.49	6.28	2.66	3.33	2.65	2.33	4.51	0	0	0	0	0	0	0	25	0	0	45	0
35	GF	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
36	OR	4.56	5.82	1.55	2.1	1.44	-1.00	3.25	0	55	0	0	10	0	0	60	5	20	15	0
37	CA	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
38	JT	3.59	4.97	2.79	2.99	2.25	1.72	6.44	0	0	0	0	0	0	0	0	0	0	5	0
39	JB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
40	DW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
41	DH	4.33	7.73	5.43	6.87	4.94	2.92	4.45	0	0	0	0	0	0	20	0	0	40	5	0
42	DM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
43	DR	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
44	RG	5.39	5.04	3.83	3.5	3.26	2.38	2.2	0	0	0	0	0	0	0	0	0	0	0	0
45	ST	2.26	6.09	2.19	5.04	4.16	3.06	3.59	10	5	0	0	0	0	0	0	0	0	0	0
46	CS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
47	RP	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
48	RB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

table A4 - 2 hand assessment results for operated hands

WEEKS 8 + POST SURGERY

patient		tip	lateral	index	middle	ring	little	skin	index			middle			ring			little		
		pinch	pinch	grasp	grasp	grasp	grasp	shear	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
1	TG	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	DS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
3	JI	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
4	RB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5	JD	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	DM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
7	EF	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
8	JL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
9	SM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
10	AH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
11	JW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
12	AC	3.92	8.21	1.59	0.71	1.65	1.45	3.80	0	0	0	15	15	0	0	35	0	5	45	0
13	SH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
14	RS	4.23	5.54	2.00	1.77	1.69	1.07	2.60	0	0	0	0	0	0	0	15	0	15	40	0
15	EM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
16	TH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
17	AS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
18	JH	1.83	5.72	1.39	2.24	1.29	0.81	2.45	0	0	0	0	0	0	0	0	0	0	5	0
19	JL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
20	RM	5.55	4.18	9.03	7.95	5.75	3.53	2.99	0	0	0	15	0	0	10	0	0	0	0	0
21	HO	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
22	JC	4.55	8.10	4.74	5.43	4.63	4.40	4.29	0	0	0	0	25	0	0	45	0	0	20	0
23	WM	6.66	8.62	4.63	3.41	3.33	2.82	4.06	0	0	0	0	0	0	0	0	0	0	0	0
24	JA	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

table A4 - 2   hand assessment results for operated hands

WEEKS 8 + POST SURGERY

patient		tip	lateral	index	middle	ring	little	skin	index			middle			ring			little		
		pinch	pinch	grasp	grasp	grasp	grasp	shear	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
25	NF	5.98	8.06	5.69	5.37	4.52	4.00	7.59	0	0	0	0	15	0	0	0	0	0	25	0
26	ED	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
27	GL	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
28	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
29	NM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
30	JW	3.48	6.45	2.94	2.88	2.78	1.97	4.42	0	0	0	0	0	0	5	25	0	0	0	0
31	WC	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
32	AC	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
33	PG	4.90	6.38	3.18	5.54	4.16	2.58	7.96	0	30	0	0	0	0	0	0	0	0	0	0
34	JS	5.34	7.66	3.95	3.51	2.41	3.18	11.02	0	0	0	0	0	0	5	35	0	0	70	0
35	GF	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
36	OR	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
37	CA	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
38	JT	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
39	JB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
40	DW	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
41	DH	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
42	DM	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
43	DR	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
44	RG	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
45	ST	1.16	5.25	1.90	5.48	4.47	4.25	-1.00	0	0	0	0	0	0	0	0	0	0	0	0
46	CS	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
47	RP	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
48	RB	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

table A4 - 2 hand assessment results for operated hands

spss3.xls

table A4 - 3

tip pinch	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.40	8.90	7.50	5.33	0.23	1.55	0.22	0.51
weeks 2 - 4	1.15	9.99	8.84	4.10	0.30	2.07	1.17	1.36
weeks 4 - 6	2.07	10.34	8.27	4.33	0.29	1.74	1.91	4.85
weeks 6 - 8	1.76	8.01	6.25	4.47	0.23	1.50	0.35	0.01
weeks 8 +	1.16	6.67	5.50	4.21	0.54	1.72	-0.54	-0.18

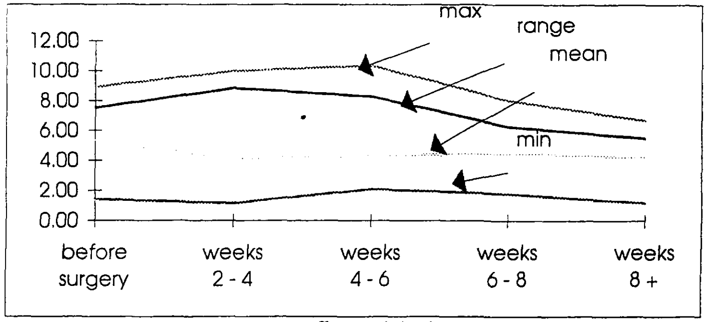


figure A4 - 1

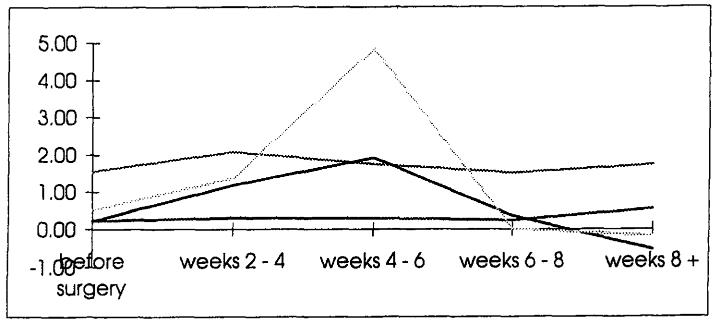


figure A4 - 2

table A4 - 4

lateral pinch	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	4.55	13.03	8.48	7.83	0.27	1.87	0.38	0.37
weeks 2 - 4	1.39	10.08	8.69	5.50	0.30	2.08	0.31	-0.19
weeks 4 - 6	2.57	9.35	6.78	6.26	0.26	1.54	-0.03	0.44
weeks 6 - 8	2.02	10.94	8.92	6.61	0.33	1.76	-0.05	1.25
weeks 8 +	5.25	8.62	3.37	7.00	0.40	1.26	-0.14	-1.88

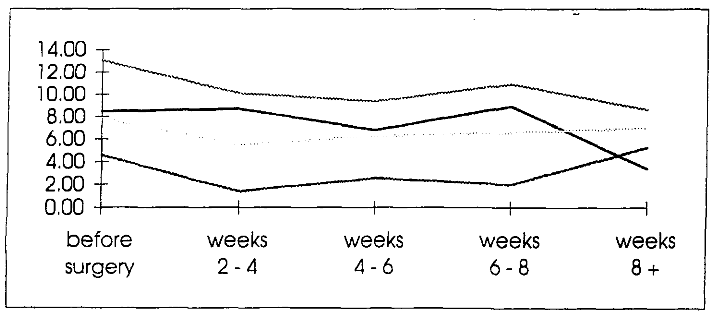


figure A4 - 3

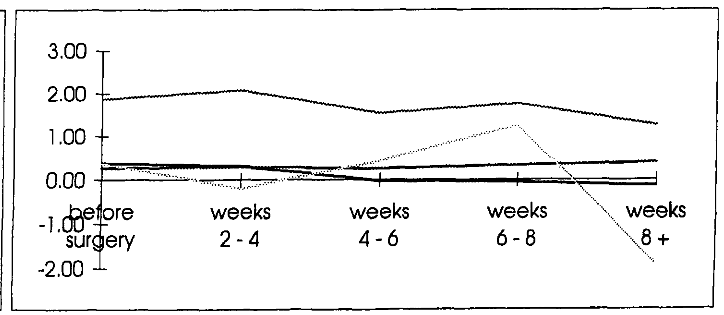


figure A4 - 4

index finger grasp	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.55	9.29	7.74	4.73	0.28	1.92	0.44	-0.32
weeks 2 - 4	0.68	8.76	8.08	3.01	0.21	1.47	1.41	3.82
weeks 4 - 6	1.25	5.49	4.24	3.40	0.19	1.16	-0.02	-0.78
weeks 6 - 8	0.85	5.83	4.98	3.51	0.27	1.44	0.17	-0.87
weeks 8 +	1.39	5.69	4.30	3.20	0.47	1.50	0.34	-1.28

table A4 - 5

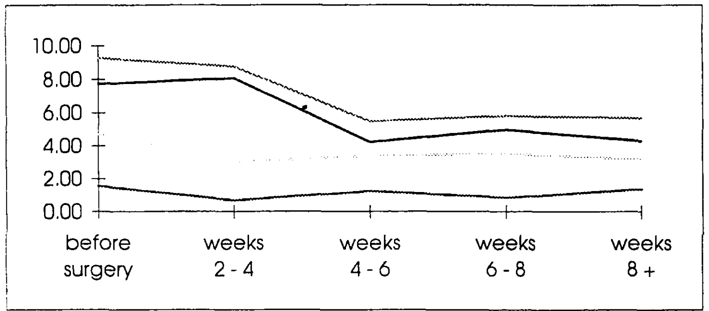


figure A4 - 5

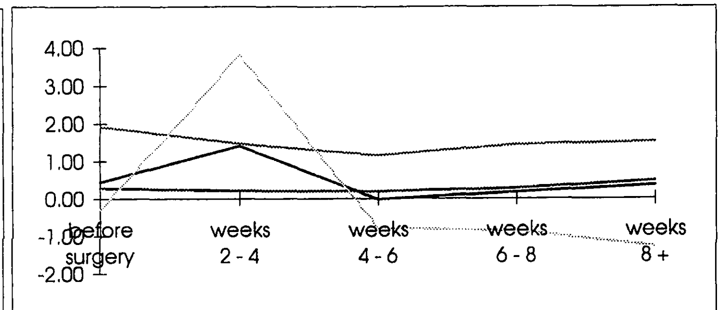


figure A4 - 6

middle finger grasp	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.14	9.41	8.27	4.53	0.28	1.87	0.49	-0.02
weeks 2 - 4	0.28	6.65	6.37	2.44	0.20	1.34	1.08	1.24
weeks 4 - 6	1.50	7.40	5.90	3.26	0.24	1.39	0.95	1.11
weeks 6 - 8	1.66	6.87	5.21	3.60	0.28	1.49	0.75	-0.29
weeks 8 +	0.71	5.54	4.83	3.63	0.56	1.76	-0.27	-1.30

table A4 - 6

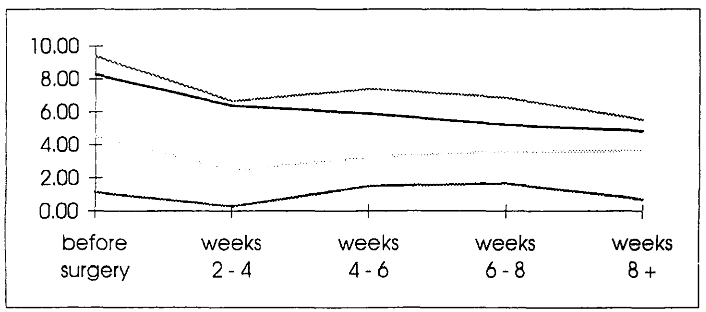


figure A4 - 7

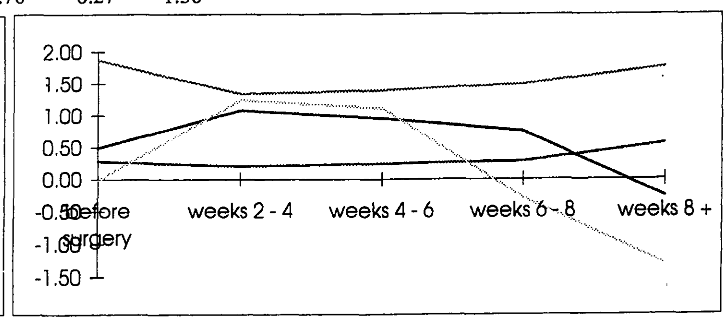


figure A4 - 8

ring finger grasp	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.03	7.35	6.32	3.83	0.25	1.64	0.42	-0.52
weeks 2 - 4	0.53	5.66	5.13	2.07	0.17	1.13	0.87	0.97
weeks 4 - 6	1.07	4.70	3.72	2.61	0.18	1.08	0.30	-1.12
weeks 6 - 8	1.12	5.78	4.66	2.96	0.23	1.20	0.57	-0.49
weeks 8 +	1.29	4.63	3.34	3.09	0.41	1.31	-0.10	-1.82

table A4 - 7

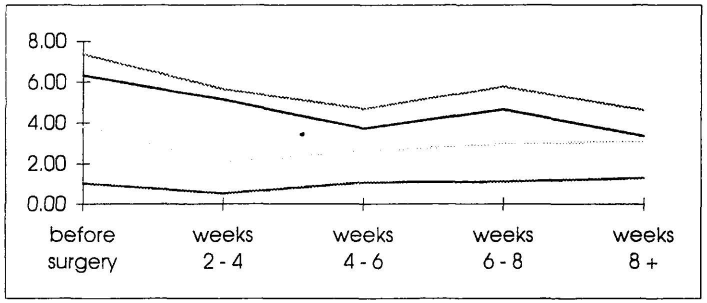


figure A4 - 9

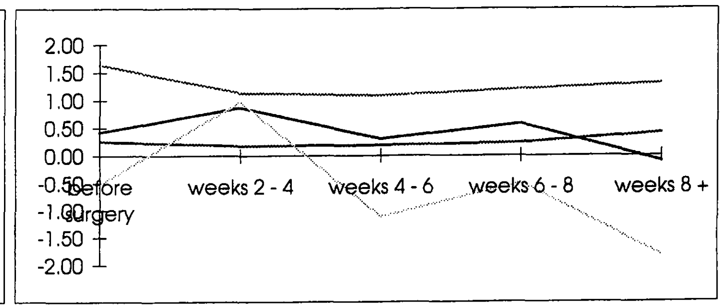


figure A4 - 10

little finger grasp	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.01	8.91	7.90	3.48	0.27	1.73	1.36	2.09
weeks 2 - 4	0.15	7.87	7.72	2.00	0.21	1.41	2.40	7.67
weeks 4 - 6	0.65	5.48	4.83	2.19	0.16	0.91	1.18	3.86
weeks 6 - 8	1.14	6.11	4.97	2.42	0.22	1.13	1.48	3.09
weeks 8 +	0.81	4.40	3.59	2.66	0.42	1.31	-0.02	-1.46

table A4 - 8

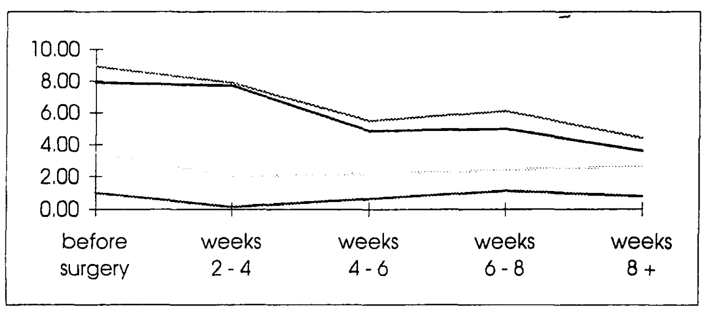


figure A4 - 11

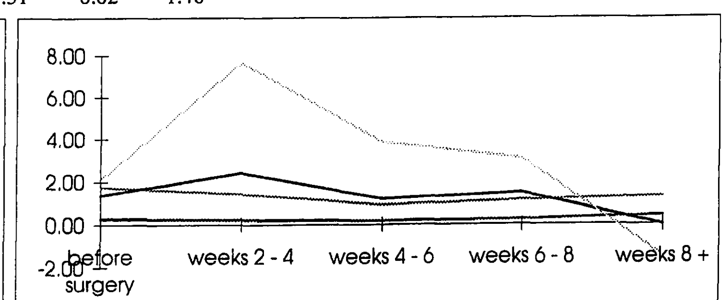


figure A4 - 12

skin shear	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	1.79	10.94	9.15	5.58	0.32	2.17	0.64	0.11
weeks 2 - 4	-0.13	6.16	6.32	2.71	0.23	1.50	0.39	0.00
weeks 4 - 6	0.58	10.21	9.63	3.76	0.33	1.97	1.21	2.33
weeks 6 - 8	0.79	8.16	7.37	4.40	0.35	1.86	-0.02	-0.55
weeks 8 +	2.45	11.02	8.57	5.24	0.98	2.93	1.11	0.24

table A4 - 9

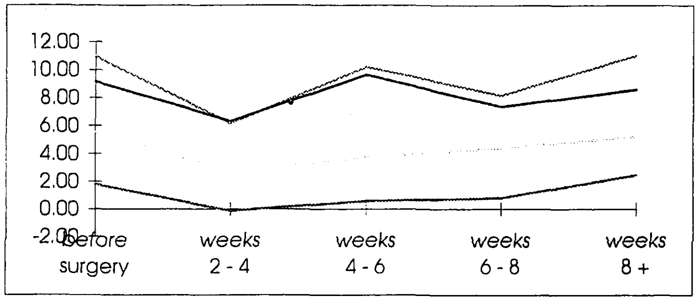


figure A4 - 13

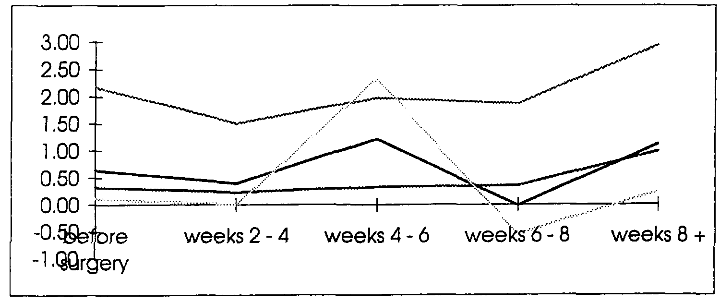


figure A4 - 14

index finger PIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	55	55	4.36	1.68	11.55	3.09	9.65
weeks 2 - 4	0	50	50	2.87	1.57	10.77	3.99	15.40
weeks 4 - 6	0	50	50	4.57	2.06	12.21	2.92	8.06
weeks 6 - 8	0	55	55	4.47	1.88	11.61	3.17	10.46
weeks 8 +	0	30	30	3.00	3.00	9.49	3.16	10.00

table A4 - 10

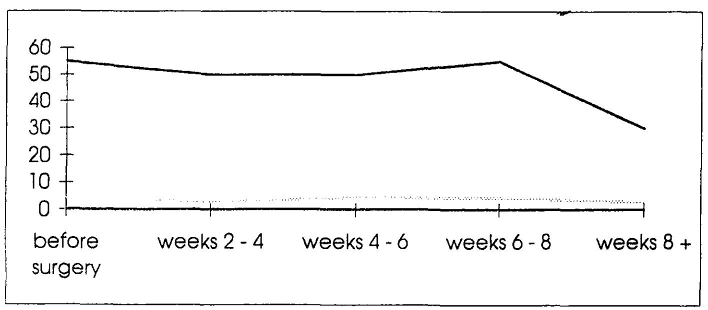


figure A4 - 15

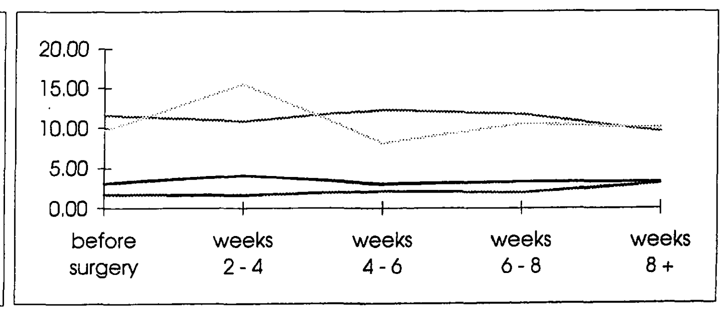


figure A4 - 16

index finger DIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	5	5	0.11	0.11	0.73	6.86	47.00
weeks 2 - 4	0	5	5	0.11	0.11	0.73	6.86	47.00
weeks 4 - 6	0	5	5	0.14	0.14	0.85	5.92	35.00
weeks 6 - 8	0	0	0	0.00	0.00	0.00	0.00	0.00
weeks 8 +	0	0	0	0.00	0.00	0.00	0.00	0.00

table A4 - 11

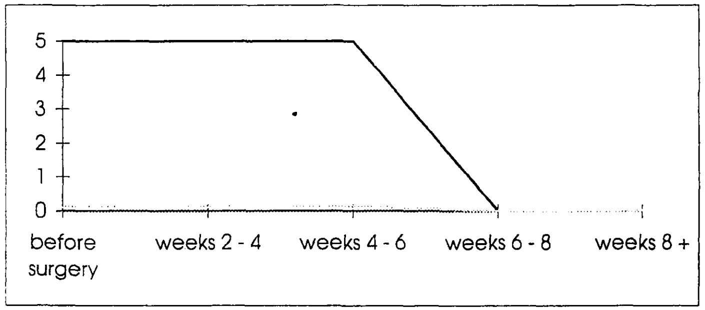


figure A4 - 17

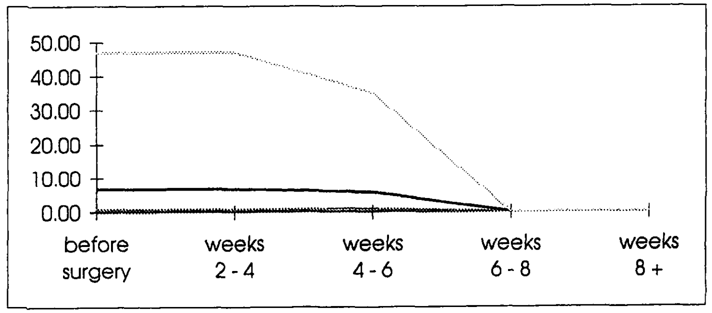


figure A4 - 18

middle finger MCP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	-20	55	75	9.68	2.28	15.62	0.79	0.07
weeks 2 - 4	0	50	50	2.23	1.26	8.65	4.65	22.60
weeks 4 - 6	0	15	15	0.71	0.51	3.01	4.26	17.83
weeks 6 - 8	0	35	35	2.24	1.19	7.32	3.57	12.77
weeks 8 +	0	15	15	1.50	1.50	4.74	3.16	10.00

table A4 - 12

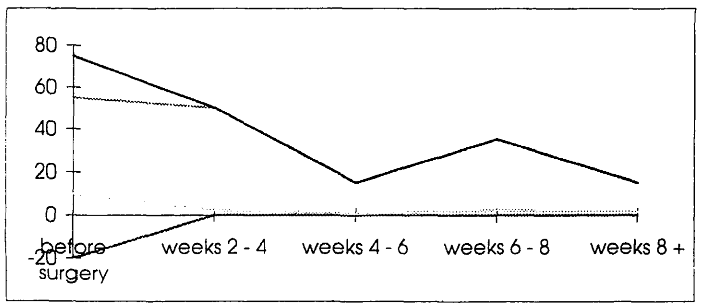


figure A4 - 19

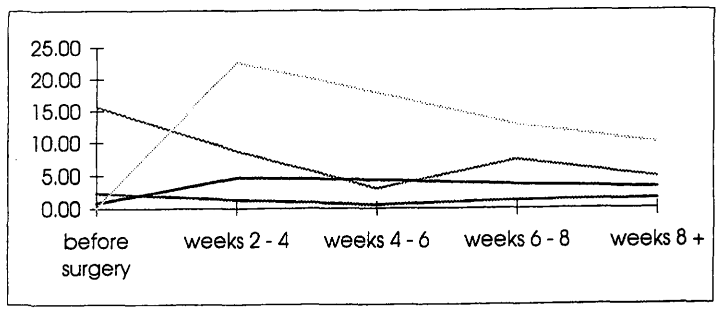


figure A4 - 20

middle finger PIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	75	75	9.26	2.60	17.85	2.36	5.24
weeks 2 - 4	0	35	35	4.04	1.38	9.48	2.39	4.71
weeks 4 - 6	0	40	40	5.71	1.81	10.72	1.74	2.08
weeks 6 - 8	0	40	40	3.95	1.49	9.17	2.58	6.53
weeks 8 +	0	25	25	5.50	2.93	9.27	1.39	0.62

table A4 - 13

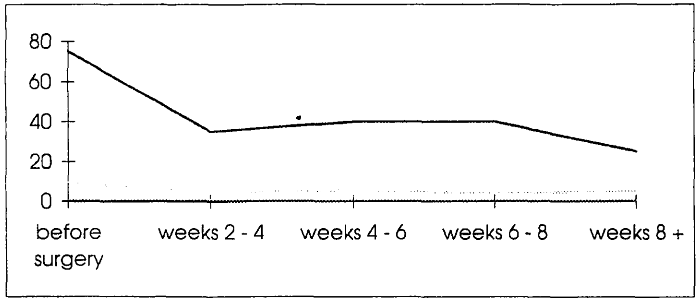


figure A4 - 21

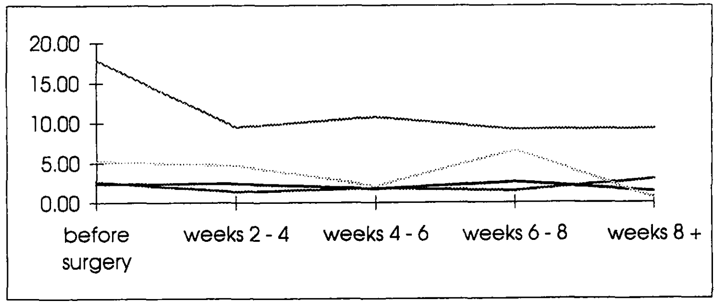


figure A4 - 22

middle finger DIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	-5	40	45	1.38	0.91	6.23	5.50	33.59
weeks 2 - 4	-5	40	45	1.38	0.97	6.65	4.96	26.55
weeks 4 - 6	-5	40	45	1.71	1.30	7.57	4.50	20.93
weeks 6 - 8	-5	40	45	0.92	1.06	6.56	6.00	36.77
weeks 8 +	0	0	0	0.00	0.00	0.00	0.00	0.00

table A4 - 14

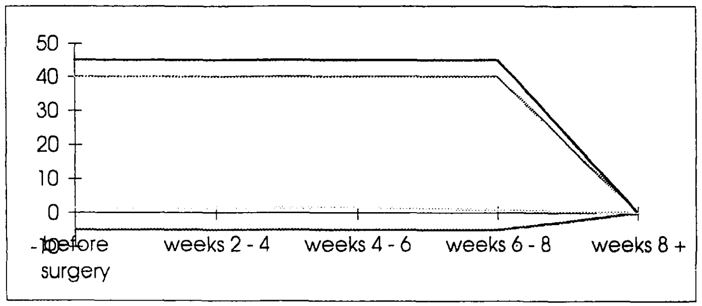


figure A4 - 23

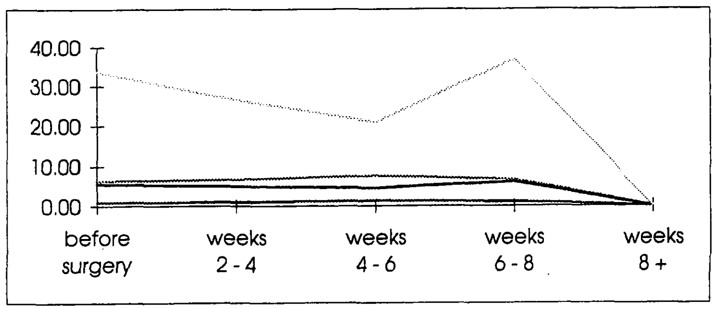


figure A4 - 24

ring finger MCP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	77	77	20.64	3.30	22.60	0.71	-0.59
weeks 2 - 4	0	45	45	3.72	1.28	8.81	3.09	10.74
weeks 4 - 6	0	25	25	1.82	0.80	4.66	4.45	21.48
weeks 6 - 8	0	35	35	3.29	1.38	8.49	2.64	6.19
weeks 8 +	0	5	5	1.00	0.67	2.11	1.78	1.41

table A4 - 15

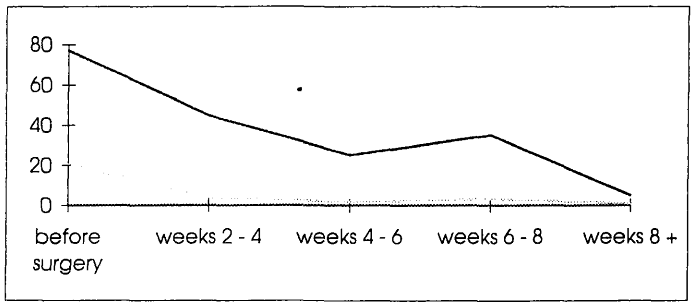


figure A4 - 25

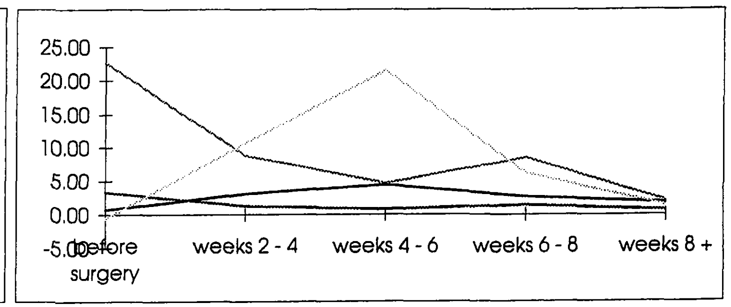


figure A4 - 26

ring finger PIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	110	110	25.32	4.55	31.18	0.97	-0.28
weeks 2 - 4	0	55	55	10.85	2.21	15.16	1.25	0.69
weeks 4 - 6	0	55	55	18.23	2.88	17.01	0.79	-0.90
weeks 6 - 8	0	60	60	10.79	2.66	16.38	1.33	0.87
weeks 8 +	0	45	45	15.50	5.69	18.02	0.54	-1.56

table A4 - 16

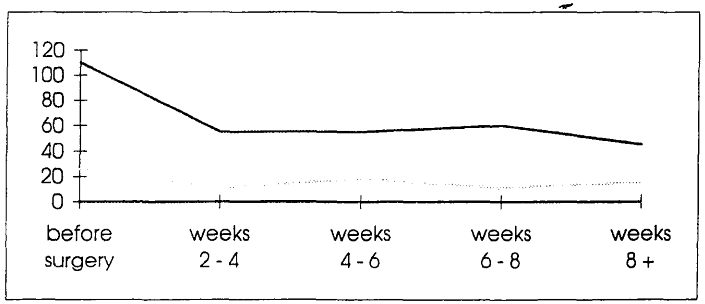


figure A4 - 27

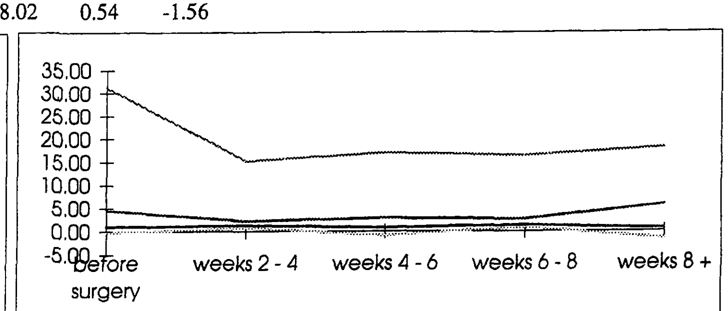


figure A4 - 28

ring finger DIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	45	45	2.34	1.17	7.99	4.22	19.05
weeks 2 - 4	0	35	35	0.96	0.77	5.28	6.20	39.84
weeks 4 - 6	0	25	25	0.71	0.71	4.23	5.92	35.00
weeks 6 - 8	0	25	25	0.92	0.68	4.17	5.54	32.21
weeks 8 +	0	0	0	0.00	0.00	0.00	0.00	0.00

table A4 - 17

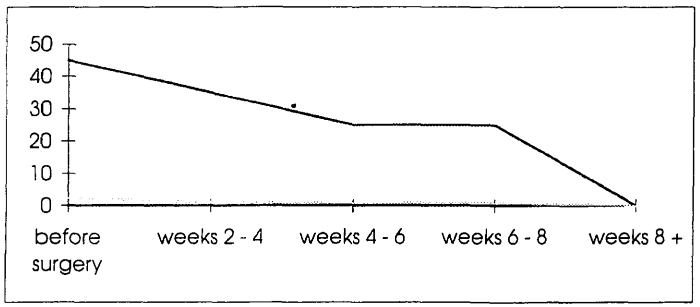


figure A4 - 29

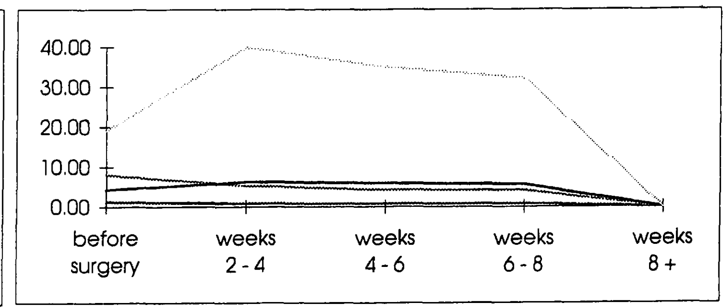


figure A4 - 30

little finger MCP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	95	95	23.98	4.21	28.55	0.82	-0.77
weeks 2 - 4	0	30	30	4.15	1.16	7.86	1.95	2.84
weeks 4 - 6	0	20	20	1.71	0.79	4.69	2.87	7.82
weeks 6 - 8	-5	40	45	3.19	1.43	8.81	2.82	8.21
weeks 8 +	0	15	15	2.00	1.53	4.83	2.66	7.19

table A4 - 18

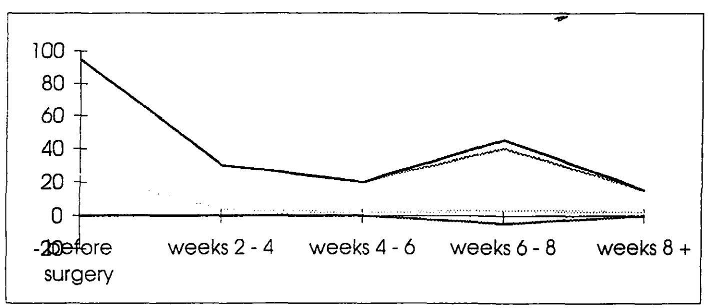


figure A4 - 31

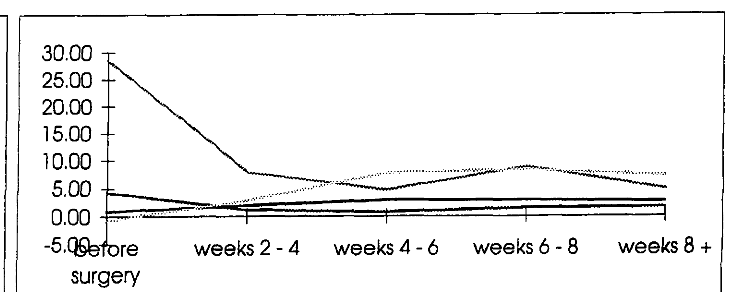


figure A4 - 32

little finger PIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	105	105	26.74	4.56	30.95	0.85	-0.56
weeks 2 - 4	0	60	60	12.45	2.59	17.75	1.45	1.14
weeks 4 - 6	0	55	55	15.14	2.89	16.74	0.93	-0.23
weeks 6 - 8	0	55	55	9.74	2.22	13.70	1.67	2.62
weeks 8 +	0	70	70	20.50	7.73	24.43	1.00	0.12

table A4 - 19

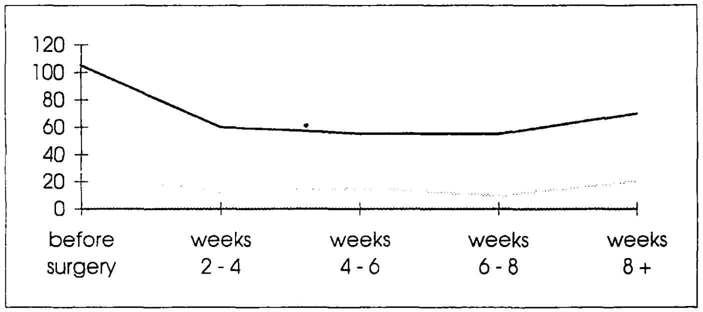


figure A4 - 33

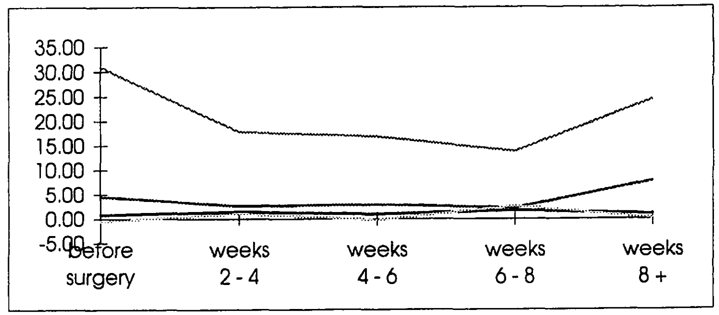


figure A4 - 34

little finger DIP	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	-25	60	85	2.72	1.86	12.64	3.25	13.33
weeks 2 - 4	0	50	50	2.77	1.47	10.12	4.09	16.46
weeks 4 - 6	0	45	45	1.29	1.29	7.61	5.92	35.00
weeks 6 - 8	0	10	10	0.39	0.29	1.79	4.85	24.25
weeks 8 +	0	0	0	0.00	0.00	0.00	0.00	0.00

table A4 - 20

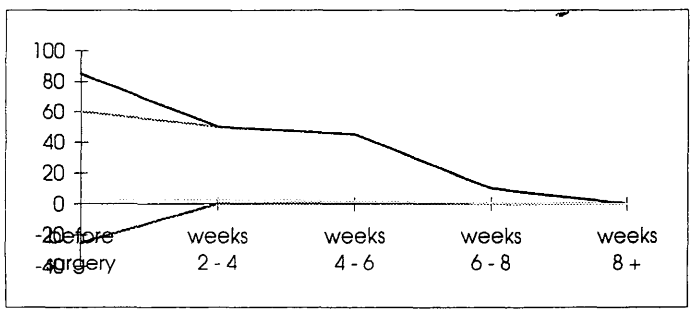


figure A4 - 35

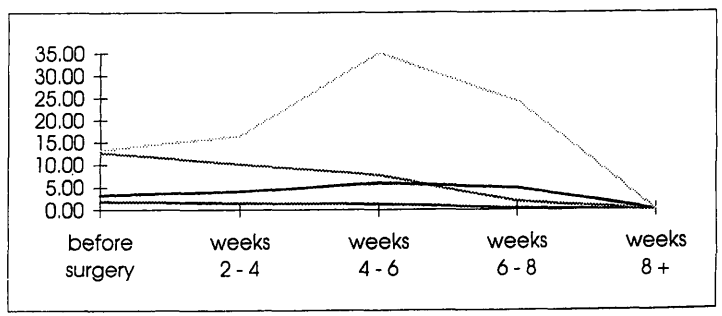


figure A4 - 36

spss4.xls

I (MCP+PIP+DIP)	0	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	55	55	5.96	1.68	11.49	2.99	6.63
weeks 2 - 4	0	55	55	5.11	2.1	14.43	2.81	6.79
weeks 4 - 6	0	55	55	5.85	2.05	14.08	2.46	5.11
weeks 6 - 8	0	55	55	6.17	1.94	13.28	2.28	4.61
weeks 8 +	0	55	55	5.43	1.89	12.97	2.5	5.64

table A4 - 21

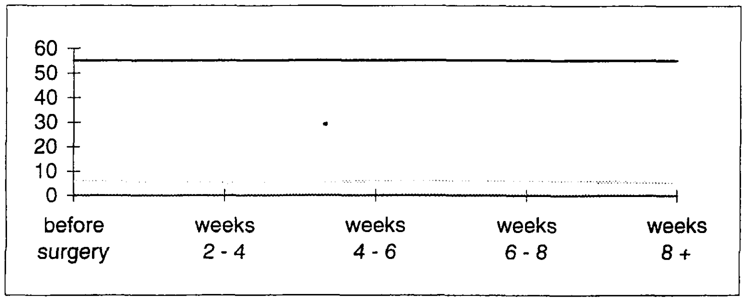


figure A4 - 37

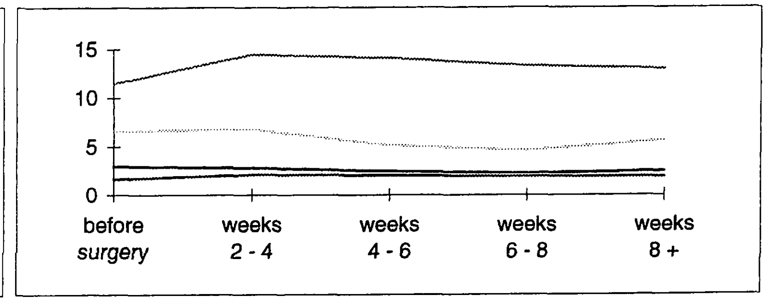


figure A4 - 38

M (MCP+PIP+DIP)	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	-5	105	110	20.32	3.57	24.48	1.35	1.86
weeks 2 - 4	0	55	55	7.66	2.17	14.89	1.87	2.39
weeks 4 - 6	0	50	50	7.98	2.15	14.73	1.68	1.47
weeks 6 - 8	0	45	45	8.51	2.02	13.87	1.38	0.49
weeks 8 +	0	45	45	9.05	2.08	14.24	1.25	0.05

table A4 - 22

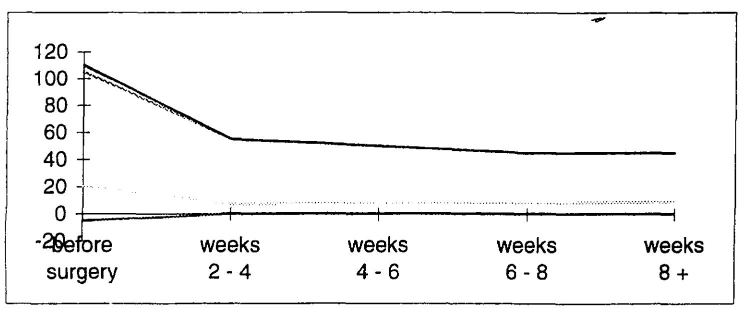


figure A4 - 39

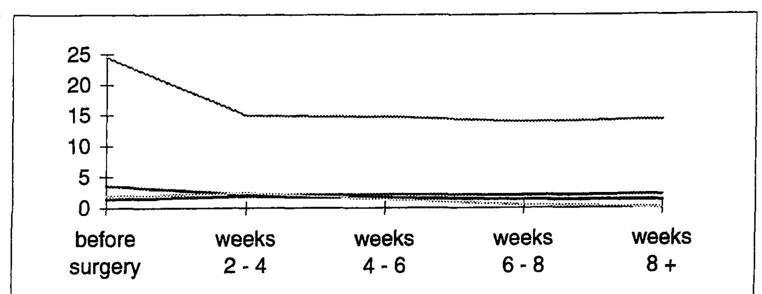


figure A4 - 40

R (MCP+PIP+DIP)	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	152	152	48.3	6.74	46.23	0.61	-0.68
weeks 2 - 4	0	85	85	15.53	3.11	21.3	1.58	2.24
weeks 4 - 6	0	75	75	15.5	3.11	21.06	1.2	0.47
weeks 6 - 8	0	75	75	16.7	3.3	22.61	1.2	0.28
weeks 8 +	0	75	75	16.6	3.32	22.73	1.19	0.24

table A4 - 23

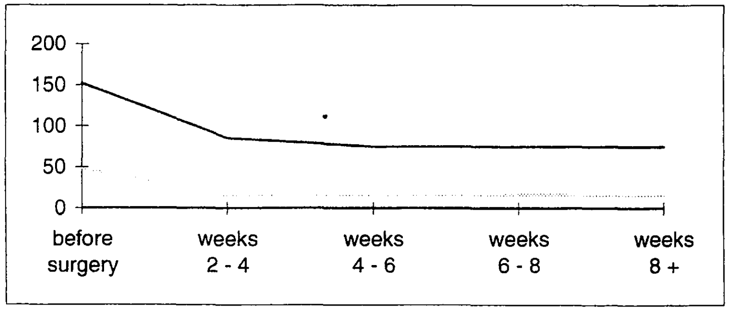


figure A4 - 41

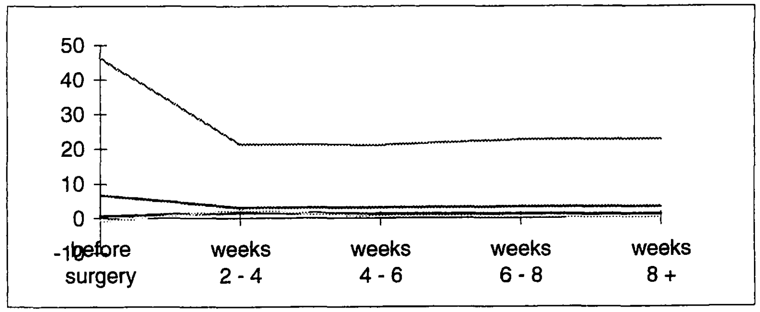


figure A4 - 42

L (MCP+PIP+DIP)	min	max	range	mean	std error	std dev	skew	kurtosis
before surgery	0	175	175	53.44	8.15	55.3	0.86	-0.5
weeks 2 - 4	0	100	100	19.36	3.81	26.12	1.67	2.41
weeks 4 - 6	0	90	90	20.21	3.29	22.58	1.42	2.13
weeks 6 - 8	0	90	90	19.79	3.37	23.1	1.4	1.88
weeks 8 +	0	90	90	20.96	3.56	24.58	1.27	1.02

table A4 - 24

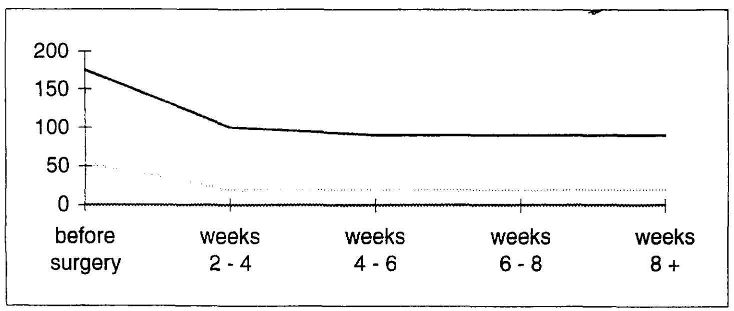


figure A4 - 43

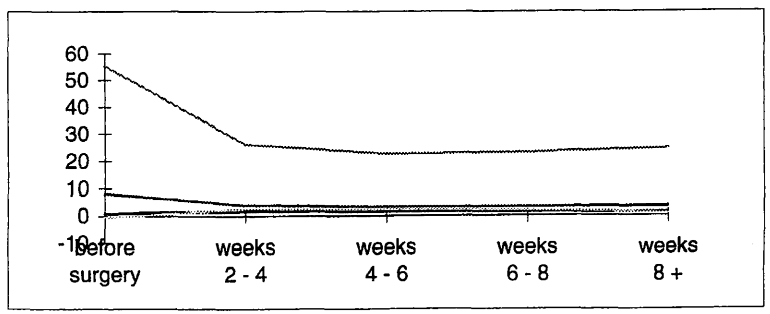


figure A4 - 44

Sum of the MCP, PIP and DIP angles

patient	pre-surgery ring finger	pre-surgery little finger	2-4 wks ring finger	2-4 wks little finger	4-6 wks ring finger	4-6 wks little finger	6-8 wks ring finger	6-8 wks little finger	8+ wks ring finger	8+ wks little finger
1	0	135	0	20	0	0	-1	-1	-1	-1
2	90	0	25	0	25	20	30	30	-1	-1
3	85	165	20	25	20	20	20	15	-1	-1
4	0	130	0	35	-1	-1	-1	-1	-1	-1
5	70	110	-1	-1	-1	-1	-1	-1	-1	-1
6	0	75	0	15	0	25	-1	-1	-1	-1
7	0	10	0	0	0	0	0	0	-1	-1
8	85	0	45	30	-1	-1	0	0	-1	-1
9	0	80	0	15	-1	-1	-1	-1	-1	-1
10	0	-1	30	30	25	25	30	30	-1	-1
11	150	0	25	0	-1	-1	65	25	-1	-1
12	95	105	55	70	35	45	-1	-1	35	50
13	0	0	0	0	0	10	0	10	-1	-1
14	50	140	25	30	20	45	20	30	15	55
15	0	10	0	0	0	0	-1	-1	-1	-1
16	0	15	-1	-1	-1	-1	-1	-1	-1	-1
17	10	100	-1	-1	-1	-1	-1	-1	-1	-1
18	0	20	0	5	0	5	0	5	0	5
19	50	15	0	0	-1	-1	0	0	-1	-1
20	75	0	30	0	45	10	55	20	10	0
21	95	10	30	0	35	0	35	0	-1	-1
22	95	10	25	5	40	5	45	20	45	20
23	105	0	0	0	0	0	0	0	0	0
24	135	155	85	100	65	55	-1	-1	-1	-1
25	50	110	10	20	10	30	5	25	0	25
26	40	45	5	0	5	5	0	10	-1	-1
27	50	0	0	0	0	0	-1	-1	-1	-1
28	0	60	-1	-1	-1	-1	-1	-1	-1	-1
29	115	10	15	35	40	20	25	10	-1	-1
30	75	20	25	0	30	0	40	0	30	0
31	30	75	0	5	0	10	0	0	-1	-1
32	0	0	0	0	-1	-1	-1	-1	-1	-1
33	0	40	0	0	0	0	0	0	0	0
34	50	145	25	30	30	40	25	45	40	70
35	150	20	75	60	-1	-1	-1	-1	-1	-1
36	120	175	45	25	55	35	70	35	-1	-1
37	0	0	0	0	0	0	-1	-1	-1	-1
38	0	60	0	0	0	10	0	5	-1	-1
39	20	50	20	15	20	20	-1	-1	-1	-1
40	80	115	-1	-1	-1	-1	-1	-1	-1	-1
41	70	170	15	20	-1	-1	20	45	-1	-1
42	30	45	15	90	-1	-1	-1	-1	-1	-1
43	45	20	25	25	-1	-1	-1	-1	-1	-1
44	35	5	0	0	0	0	0	0	-1	-1
45	0	10	0	0	0	0	0	0	0	0
46	50	55	0	0	0	5	-1	-1	-1	-1
47	115	50	60	0	60	25	-1	-1	-1	-1
48	0	0	0	0	0	0	-1	-1	-1	-1

	pre-surgery	2-4 wks	4-6 wks	6-8 wks	8+ wks
patients:	48	43	33	26	10
set:	1		2		3

table A4-25

Appendix 5

Results of the application of the twin actuator machine upon Berlin patients

Appendix 5.1

Original data - active ranges in finger joint angles; pre- and post- each CPM treatment

Patient: RB (#1) ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT - extension/neutral/flexion method

	TIME	13/1			15/01 9.05 (before)			9.50 (after)			16/01 13.05 (before)			15.00 (after)			20/01 13.10 (before)			14.55 (after)			21/01 13.00 (before)			15.00 (after)		
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 2	10	0	50	10	0	55	0	0	60	0	0	55	0	0	60	0	0	55	0	0	55	0	0	65	0	0	65
2 - neutral	MCP 3	10	0	55	10	0	60	0	0	60	0	20	65	0	20	65	0	0	65	0	0	65	0	0	60	0	0	65
3 - flexion	MCP 4	15	0	50	10	0	45	10	0	45	10	0	60	10	0	60	0	0	50	0	0	50	0	0	50	0	0	60
	MCP 5	10	0	30	5	0	30	5	0	30	20	0	35	20	0	40	15	0	45	15	0	50	15	0	45	10	0	45
1 - neutral	PIP 2	0	0	55	0	0	65	0	0	65	0	0	75	0	0	80	0	0	80	0	0	80	0	0	75	0	0	80
2 - extension	PIP 3	0	5	70	0	5	70	0	10	65	0	0	95	0	0	95	0	0	90	0	0	95	0	0	90	0	0	90
3 - flexion	PIP 4	0	5	80	0	5	75	0	10	75	0	5	90	0	5	90	0	0	90	0	0	95	0	0	90	0	0	90
	PIP 5	0	15	85	0	10	70	0	15	75	0	10	80	0	10	90	0	15	85	0	10	85	0	15	90	0	10	90
1 - neutral	DIP 2	0	10	40	0	10	35	0	10	40	0	0	45	0	0	50	0	10	50	0	10	50	0	5	65	0	5	70
2 - extension	DIP 3	0	25	30	0	20	35	0	20	30	0	20	30	0	20	40	0	20	30	0	10	40	0	10	40	0	10	40
3 - flexion	DIP 4	0	15	20	0	15	25	0	15•	30	0	15	35	0	10	40	0	5	30	0	5	30	0	5	30	0	5	35
	DIP 5	0	10	40	0	10	40	0	10	30	0	10	40	0	5	40	0	10	40	0	10	40	0	5	40	0	5	40

(27)

	TIME	22/01 13.15 (before)			15.05 (after)			23/01 13.10 (before)			15.30 (after)			24/01 13.00 (before)			15.15 (after)			27/01 13.05 (before)			15.30 (after)			28/01 13.20 (before)			15.40 (after)		
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 2	0	0	55	0	0	65	10	0	60	0	0	60	0	0	60	0	0	60	10	0	60	10	0	60	5	0	55	5	0	60
2 - neutral	MCP 3	0	0	60	0	0	70	0	0	65	0	0	65	0	0	65	0	0	65	15	0	60	15	0	70	5	0	60	5	0	60
3 - flexion	MCP 4	0	0	55	0	0	60	0	0	50	0	0	55	0	0	50	0	0	55	10	0	55	10	0	60	5	0	60	10	0	55
	MCP 5	10	0	45	5	0	45	20	0	50	20	0	50	10	0	50	15	0	50	5	0	50	15	0	50	15	0	55	15	0	55
1 - neutral	PIP 2	0	0	80	0	0	80	0	0	80	0	0	75	0	0	75	0	0	75	0	5	70	0	5	75	0	0	75	0	10	75
2 - extension	PIP 3	0	0	90	0	0	100	0	0	85	0	0	85	0	0	90	0	0	80	0	5	85	0	5	85	0	5	90	0	10	85
3 - flexion	PIP 4	0	0	95	0	0	95	0	0	95	0	0	95	0	0	95	0	0	95	0	5	95	0	5	95	0	15	95	0	15	95
	PIP 5	0	10	90	0	10	90	0	20	85	0	25	85	0	20	85	0	20	85	0	30	80	0	20	80	0	25	85	0	25	85
1 - neutral	DIP 2	0	5	55	0	5	60	0	20	50	0	20	45	0	25	45	0	20	45	0	20	40	0	20	40	0	20	45	0	25	40
2 - extension	DIP 3	0	10	40	0	25	35	0	30	35	0	30	30	0	30	30	0	·30	30	0	25	25	0	25	30	0	25	35	0	25	35
3 - flexion	DIP 4	0	5	30	0	5	30	0	10	30	0	10	30	0	15	30	0	20	30	0	15	25	0	15	25	0	15	30	0	10	30
	DIP 5	0	5	30	0	5	40	0	15	40	0	15	40	0	20	40	0	20	40	0	15	35	0	15	40	0	20	35	0	15	30

(53)

	TIME	29/01 13.30 (before)			15.40 (after)			30/01 13.30 (before)			15.45 (after)			03/02 13.00 (before)			14.10(1)/15.15(2)			04/02 12.55 (before)			14.05(1)/15.05(2)			05/02 13.25 (before)			14.35/15.45		
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 2	5	0	50	5	0	50	5	0	55	5	0	60	5	0	65	0	0	55	0	0	60	0	0	65	0	0	45	0	0	60
2 - neutral	MCP 3	10	0	50	10	0	60	10	0	60	10	0	55	10	0	60	10	0	60	10	0	45	10	0	65	10	0	45	5	0	60
3 - flexion	MCP 4	10	0	45	10	0	50	10	0	65	10	0	50	10	0	55	'5	0	55	5	0	55	10	0	60	5	0	45	5	0	60
	MCP 5	15	0	45	15	0	45	15	0	35	15	0	50	15	0	50	15	0	45	15	0	45	15	0	55	15	0	45	15	0	60
1 - neutral	PIP 2	0	10	75	0	10	65	0	0	75	0	0	75	0	0	65	0	0	70	0	0	65	0	5	75	0	0	70	0	5	65
2 - extension	PIP 3	0	10	75	0	10	70	0	5	80	0	5	75	0	5	75	0	5	75	0	5	75	0	5	80	0	5	80	0	5	80
3 - flexion	PIP 4	0	15	80	0	15	75	0	10	85	0	10	85	0	10	80	0	10	85	0	10	80	0	10	90	0	10	85	0	10	80
	PIP 5	0	25	70	0	20	80	0	15	75	0	15	70	0	15	70	0	15	75	0	20	75	0	10	75	0	15	80	0	15	85
1 - neutral	DIP 2	0	10	45	0	10	50	0	10	45	0	10	45	0	10	45	0	10	40	0	20	35	0	10	45	0	20	40	0	15	35
2 - extension	DIP 3	0	10	35	0	20	40	0	20	30	0	20	30	0	20	30	0	20	35	0	25	30	0	25	35	0	25	35	0	25	35
3 - flexion	DIP 4	0	20	30	0	10	30	0	10	20	0	15	25	0	15	30	0	15	30	0	15	25	0	15	30	0	10	25	0	10	25
	DIP 5	0	15	30	0	20	40	0	20	35	0	20	25	0	20	40	0	20	25	0	20	30	0	15	35	0	15	35	0	20	35

(ap5-1.xls)

(79)

		07/02						10/02						11/02						12/02						13/02					
	TIME	13.20 (*before*)			14.25/15.3 (*after*)			13.10 (*before*)			?/15.45			13.10 (*before*)			14.15 (*after*)			13.20 (*before*)			14.20/15.45			13.25 (*before*)			13.30/15.45		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	60	0	0	65	0	0	60	0	0	60	0	0	60	0	5	55	0	0	60	0	0	65	0	0	55	0	0	75
2 - neutral	MCP 3	5	0	60	5	0	70	5	0	70	5	0	70	5	0	60	5	0	70	5	0	65	5	0	70	5	0	60	5	0	70
3 - flexion	MCP 4	5	0	55	5	0	60	10	0	55	5	0	55	5	0	45	0	0	45	5	0	50	5	0	60	5	0	50	5	0	60
	MCP 5	15	0	55	15	0	65	15	0	50	15	0	50	15	0	45	15	0	65	15	0	50	10	0	65	15	0	45	10	0	60
1 - neutral	PIP 2	0	0	65	0	5	65	0	0	75	0	0	80	0	0	70	0	0	65	0	0	70	0	0	70	0	0	60	0	0	70
2 - extension	PIP 3	0	5	75	0	5	75	0	0	90	0	0	85	0	5	80	0	5	75	0	5	80	0	5	80	0	5	70	0	5	80
3 - flexion	PIP 4	0	5	80	0	10	80	0	10	95	0	5	100	0	5	95	0	5	75	0	5	75	0	5	75	0	5	75	0	5	90
	PIP 5	0	15	80	0	15	70	0	15	85	0	15	85	0	15	80	0	15	75	0	15	75	0	15	75	0	15	75	0	15	80
1 - neutral	DIP 2	0	15	45	0	15	45	0	15	50	0	10	30	0	15	40	0	15	40	0	15	35	0	15	40	0	15	35	0	15	40
2 - extension	DIP 3	0	25	30	0	25	30	0	30	30	0	15	30	0	25	30	0	25	30	0	25	30	0	25	35	0	25	30	0	25	35
3 - flexion	DIP 4	0	15	30	0	15	30	0	10	30	0	10	35	0	15	25	0	15	25	0	15	25	0	15	30	0	15	30	0	15	25
	DIP 5	0	20	35	0	20	30	0	10	35	0	10	25	0	20	35	0	20	45	0	25	25	0	20	25	0	25	25	0	10	35

(105)

		14/02						17/02						18/02						27/02						28/02					
	TIME	13.25 (*before*)			14.30/15.45			13.15 (*before*)			?/15.30			12.55 (*before*)			14.00/15.30			13.00 (*before*)			14.00/15.30			13.00 (*before*)			13.10/15.15		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	60	0	0	65	0	0	60	0	0	55	0	0	55	0	0	60	0	0	50	0	0	60	0	0	55	0	0	60
2 - neutral	MCP 3	5	0	60	5	0	70	0	0	60	0	0	65	5	0	55	5	0	60	0	0	55	5	0	60	0	0	55	0	0	60
3 - flexion	MCP 4	5	0	55	5	0	55	0	0	50	0	0	60	10	0	50	10	0	55	0	0	50	0	0	55	5	0	45	10	0	50
	MCP 5	15	0	45	15	0	60	10	0	40	15	0	60	15	0	50	15	0	50	15	0	35	20	0	50	15	0	45	10	0	70
1 - neutral	PIP 2	0	0	70	0	0	60	0	0	70	0	0	70	0	0	70	0	0	75	0	0	70	0	0	65	0	0	65	0	5	60
2 - extension	PIP 3	0	5	75	0	5	60	0	5	75	0	5	75	0	0	75	0	0	80	0	0	75	0	0	75	0	5	70	0	10	75
3 - flexion	PIP 4	0	5	80	0	5	75	0	10	80	0	10	90	0	10	80	0	5	85	0	0	80	0	0	80	0	0	75	0	10	80
	PIP 5	0	15	75	0	15	65	0	30	85	0	30	80	0	20	70	0	25	75	0	20	80	0	20	80	0	15	65	0	20	65
1 - neutral	DIP 2	0	15	35	0	15	40	0	15	40	0	20	50	0	20	35	0	15	40	0	20	35	0	15	40	0	10	30	0	10	40
2 - extension	DIP 3	0	25	30	0	25	30	0	25	30	0	30	30	0	25	30	0	25	35	0	30	35	0	15	30	0	25	30	0	25	30
3 - flexion	DIP 4	0	10	20	0	10	25	0	10	20	0	10	30	0	10	20	0	15	20	0	15	30	0	10	30	0	5	20	0	10	20
	DIP 5	0	15	30	0	15	30	0	15	30	0	15	40	0	10	30	0	15	30	0	15	40	0	15	40	0	5	25	0	10	30

(131)

		02/03						03/03						04/03						09/03						10/03					
	TIME	13.00 (*before*)			14.05/15.15			13.05 (*before*)			14.20/15.15			13.00 (*before*)			14.15/15.30			13.00 (*before*)			14.10/15.15			12.55 (*before*)			? (*after*)		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	55	5	0	65	0	0	55	5	0	65	5	0	55	0	0	60	5	0	55	5	0	65	5	0	60	10	0	65
2 - neutral	MCP 3	5	0	55	5	0	60	5	0	55	10	0	65	10	0	55	10	0	65	5	0	55	10	0	65	10	0	60	10	0	60
3 - flexion	MCP 4	10	0	55	5	0	55	15	0	55	15	0	55	10	0	50	10	0	60	5	0	55	15	0	65	10	0	55	10	0	55
	MCP 5	15	0	55	10	0	55	20	0	55	10	0	55	15	0	50	15	0	50	15	0	50	15	0	55	10	0	45	15	0	60
1 - neutral	PIP 2	0	0	65	0	10	65	0	5	70	0	5	60	0	5	70	0	10	65	0	5	70	0	5	75	0	5	75	0	5	75
2 - extension	PIP 3	0	5	80	0	10	70	0	5	80	0	5	75	0	5	70	0	10	70	0	5	75	0	5	75	0	5	85	0	10	80
3 - flexion	PIP 4	0	5	85	0	5	85	0	5	80	0	5	75	0	5	80	0	10	80	0	5	85	0	5	90	0	10	90	0	10	85
	PIP 5	0	20	75	0	20	70	0	20	75	0	25	70	0	20	80	0	25	80	0	20	80	0	25	95	0	25	90	0	20	80
1 - neutral	DIP 2	0	20	30	0	15	35	0	20	45	0	20	40	0	25	45	0	20	40	0	15	35	0	10	50	0	25	50	0	15	40
2 - extension	DIP 3	0	25	30	0	25	40	0	30	35	0	25	30	0	25	30	0	25	30	0	25	25	0	30	30	0	25	30	0	30	30
3 - flexion	DIP 4	0	15	25	0	10	25	0	10	20	0	10	20	0	10	25	0	10	25	0	10	30	0	10	30	0	15	30	0	10	30
	DIP 5	0	15	20	0	10	30	0	10	30	0	10	35	0	10	35	0	15	30	0	15	40	0	10	35	0	15	35	0	10	40

(ap5-1.xls)

(157)

		11/03 12.50 (before)			11/03 14.00/15.10			12/03 13.00 (before)			12/03 14.05/15.15			13/03 12.45 (before)		
	TIME	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2	5	0	60	10	0	65	5	0	60	5	0	65	0	0	55
2 - neutral	MCP 3	5	0	60	5	0	60	5	0	55	10	0	55	0	0	55
3 - flexion	MCP 4	5	0	50	10	0	65	15	0	50	15	0	55	0	0	45
	MCP 5	15	0	40	10	0	50	10	0	50	15	0	50	10	0	40
1 - neutral	PIP 2	0	5	70	0	5	65	0	5	70	0	5	70	0	5	65
2 - extension	PIP 3	0	5	80	0	5	75	0	5	80	0	10	75	0	5	75
3 - flexion	PIP 4	0	10	90	0	10	85	0	5	90	0	10	80	0	5	75
	PIP 5	0	30	80	0	25	75	0	25	85	0	25	75	0	20	65
1 - neutral	DIP 2	0	25	45	0	20	50	0	20	50	0	10	35	0	10	35
2 - extension	DIP 3	0	30	30	0	30	30	0	30	30	0	25	25	0	25	30
3 - flexion	DIP 4	0	15	25	0	15	30	0	15	30	0	10	20	0	10	20
	DIP 5	0	10	35	0	15	35	0	15	35	0	10	25	0	10	35

		13/03 14/15.40			16/03 13.07 (before)			16/03 14.15/15.35			17/03 13.00 (before)			17/03 14.08 (after)		
	TIME	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2	0	0	60	0	0	50	5	0	60	0	0	50	5	0	60
2 - neutral	MCP 3	10	0	50	10	0	50	10	0	65	10	0	50	10	0	65
3 - flexion	MCP 4	0	0	50	15	0	40	15	0	60	15	0	45	15	0	60
	MCP 5	15	0	40	20	0	40	15	0	55	20	0	40	15	0	55
1 - neutral	PIP 2	0	5	65	0	10	70	0	10	70	0	10	70	0	10	70
2 - extension	PIP 3	0	0	75	0	0	75	0	5	75	0	0	75	0	0	75
3 - flexion	PIP 4	0	5	80	0	5	90	0	10	90	0	5	90	0	10	90
	PIP 5	0	25	75	0	20	75	0	20	75	0	20	75	0	20	75
1 - neutral	DIP 2	0	10	45	0	15	40	0	15	40	0	15	40	0	15	40
2 - extension	DIP 3	0	20	30	0	30	30	0	25	30	0	30	30	0	25	30
3 - flexion	DIP 4	0	10	30	0	10	20	0	10	25	0	10	20	0	10	25
	DIP 5	0	10	30	0	10	25	0	15	30	0	10	25	0	15	30

(183)

		18/03 13.07 (before)			18/03 14.45 (after)			19/03 13.30 (before)			19/03 14.30/15.35			20/03 13.00 (before)		
	TIME	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2	10	0	55	0	0	60	0	0	50	0	0	60	0	0	60
2 - neutral	MCP 3	0	0	60	5	0	65	10	0	55	15	0	60	5	0	60
3 - flexion	MCP 4	0	0	55	10	0	60	15	0	45	15	0	50	5	0	60
	MCP 5	5	0	45	10	0	55	10	0	45	15	0	55	15	0	50
1 - neutral	PIP 2	0	5	80	0	5	70	0	5	75	0	5	60	0	5	70
2 - extension	PIP 3	0	5	85	0	10	80	0	10	80	0	5	70	0	5	80
3 - flexion	PIP 4	0	5	90	0	10	85	0	10	50	0	5	75	0	5	85
	PIP 5	0	25	80	0	30	80	0	20	50	0	25	75	0	25	75
1 - neutral	DIP 2	0	20	50	0	10	35	0	10	35	0	20	35	0	15	45
2 - extension	DIP 3	0	30	40	0	30	30	0	30	30	0	25	30	0	25	30
3 - flexion	DIP 4	0	10	25	0	15	25	0	15	25	0	15	20	0	10	25
	DIP 5	0	10	35	0	15	45	0	15	40	0	15	35	0	10	25

		20/03 15.30 (after)			23/03 12.50 (before)			23/03 15.20 (after)			24/03 ? (before)			24/03 ? (after)		
	TIME	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2	0	0	60	0	0	55	0	0	55	5	0	60	5	0	50
2 - neutral	MCP 3	5	0	60	15	0	55	15	0	55	5	0	60	5	0	50
3 - flexion	MCP 4	10	0	60	15	0	50	15	0	50	5	0	55	5	0	45
	MCP 5	15	0	60	20	0	40	10	0	40	15	0	50	15	0	45
1 - neutral	PIP 2	0	5	75	0	10	75	0	10	75	0	5	70	0	5	75
2 - extension	PIP 3	0	5	75	0	5	85	0	10	75	0	5	70	0	5	80
3 - flexion	PIP 4	0	10	80	0	5	90	0	10	80	0	10	70	0	10	90
	PIP 5	0	15	75	0	15	80	0	20	75	0	20	65	0	20	80
1 - neutral	DIP 2	0	30	40	0	20	45	0	15	40	0	10	40	0	10	40
2 - extension	DIP 3	0	25	30	0	25	30	0	30	30	0	30	35	0	30	30
3 - flexion	DIP 4	0	10	25	0	15	25	0	15	20	0	15	20	0	10	35
	DIP 5	0	20	25	0	15	35	0	15	35	0	15	20	0	10	40

Patient: MK (#3) **ORIGINAL DATA : RANGES OF FINGER JOINT MOVEMENT**

		6/7			7/7 (before)			7/7 (after)			8/7 (before)			8/7 (after)			9/7 (before)			9/7 (after)			10/7 (before)			10/7 (after)		
	TIME	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral 2 - extension 3 - flexion	DIP 2 DIP 3 DIP 4 DIP 5	0	10	30	0	10	30	0	10	35	0	5	35	0	5	35	0	10	30	0	5	35	0	5	35	0	5	35

(40)

		14/7 (before)			14/7 (after)			15/7 (before)			15/7 (after)			16/7 (before)			16/7 (after)			17/7 (before)			17/7 (after)			20/7 (before)			20/7 (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral 2 - extension 3 - flexion	DIP 2 DIP 3 DIP 4 DIP 5	0	10	30	0	10	35	0	10	30	0	10	35	0	10	35	0	10	40	0	5	30	0	5	35	0	5	40	0	5	30

(ap5-1.xls)

(79)

		21/7 (before)			(after)		
		1	2	3	1	2	3
	DIP 2						
1 - neutral	DIP 3						
2 - extension	DIP 4	0	10	40	0	10	40
3 - flexion	DIP 5						

Patient: Z (#4)

ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT

	TIME				02/07 10 (before)			12.3 (after)			06/07 10.2 (before)			12.3 (after)			07/07 (before)			(after)			08/07 (before)			(after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	PIP 2				0	50	65	0	40	70	0	40	80	0	35	85	0	50	80	0	40	80	0	50	75	0	40	80
1 - neutral	PIP 3				0	40	75	0	40	70	0	40	75	0	50	75	0	45	70	0	35	65	0	30	85	0	35	80
2 - extension	PIP 4				0	55	65	0	55	65	0	50	75	0	40	75	0	55	70	0	50	65	0	45	75	0	50	75
3 - flexion	PIP 5				0	50	60	0	40	60	0	35	70	0	35	70	0	60	70	0	45	60	0	40	65	0	35	70

(27)

		09/07 12.3 (before)			13.15 (after)			10/07 (before)			(after)			13/07 (before)			(after)			14/07 (before)			(after)			15/07 (before)			(after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	PIP 2	0	50	80	0	50	85	0	50	85	0	45	85	0	50	80	0	50	80	0	50	90	0	40	90	0	40	90	0	50	90
1 - neutral	PIP 3	0	40	70	0	40	70	0	45	60	0	45	60	0	45	75	0	35	60	0	45	60	0	35	75	0	40	80	0	30	75
2 - extension	PIP 4	0	45	75	0	50	65	0	50	60	0	50	60	0	50	70	0	50	70	0	50	70	0	45	60	0	45	80	0	50	70
3 - flexion	PIP 5	0	45	65	0	50	70	0	50	60	0	50	55	0	50	60	0	45	70	0	35	70	0	40	60	0	50	60	0	45	60

(53)

		16/07 (before)			(after)			20/07 (before)			(after)			(before)			(after)			(before)			(after)			(before)			(after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	PIP 2	0	50	90	0	50	80	0	50	90	0	50	90																		
1 - neutral	PIP 3	0	40	70	0	40	60	0	40	80	0	45	80																		
2 - extension	PIP 4	0	45	65	0	40	70	0	40	70	0	45	70																		
3 - flexion	PIP 5	0	40	65	0	50	60	0	45	65	0	50	65																		

Patient: CB (#5)

ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT

	TIME	date			19/8 time (before)			time (after)			20/8 time (before)			time (after)			21/8 time (before)			time (after)			24/8 time (before)			time (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																											
2 - extension	PIP 4				0	30	30	0	32	50	0	30	30	0	30	40	0	30	30	0	30	40	0	25	35	0	25	40
3 - flexion	PIP 5																											

(27)

		25/8 time (before)			time (after)			26/8 time (before)			time (after)			27/8 time (before)			time (after)			28/8 time (before)			time (after)			1/9 time (before)			time (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	25	35	0	25	35	0	25	35	0	25	35	0	25	25	0	25	35	0	25	35	0	25	35	0	25	35	0	20	30
3 - flexion	PIP 5																														

(53)

		8/9						10/9						11/9						14/9						15/9					
		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	20	20	0	20	30	0	20	30	0	30	30	0	20	30	0	20	30	0	20	30	0	20	35	0	15	30	0	15	30
3 - flexion	PIP 5																														

(79)

		16/9						21/9						22/9						24/9						29/9					
		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)		time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	15	30	0	15	30	0	15	30	0	20	35	0	15	30	0	15	35	0	10	25	0	10	30	0	20	40	0	20	40
3 - flexion	PIP 5																														

Patient: AM (#6) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT**

		date			15/5						18/5						20/5						21/5					
	TIME				12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3				0	60	90	0	50	95	0	65	90	0	50	90	0	65	85	0	50	90	0	50	90	0	50	90
2 - extension	PIP 4				0	65	85	0	65	90	0	65	90	0	65	95	0	65	90	0	65	90	0	65	90	0	60	90
3 - flexion	PIP 5																											

(27)

		22/5						26/5						27/5						1/6						2/6					
	TIME	11.15	(before)		12.00	(after)		12.45	(before)		13.45	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3	0	50	90	0	45	90	0	60	95	0	50	100	0	55	95	0	50	90	0	60	90	0	55	90	0	55	90	0	50	90
2 - extension	PIP 4	0	70	90	0	70	90	0	65	95	0	65	90	0	65	90	0	55	90	0	70	90	0	70	95	0	60	90	0	60	90
3 - flexion	PIP 5																														

(53)

		3/6						4/6						9/6						10/6						11/6					
	TIME	12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3	0	60	90	0	55	90	0	60	90	0	55	90	0	50	90	0	55	90	0	60	90	0	50	90	0	60	90	0	60	90
2 - extension	PIP 4	0	70	90	0	60	90	0	70	95	0	65	95	0	70	90	0	65	90	0	70	90	0	65	90	0	75	90	0	70	90
3 - flexion	PIP 5																														

(79)

		12/6						15/6						16/6						17/6						19/6					
	TIME	11.15	(before)		12.00	(after)		12.30	(before)		13.30	(after)		12.30	(before)		13.30	(after)		12.15	(before)		13.15	(after)		13.00	(before)		13.30	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3	0	65	90	0	60	90	0	55	90	0	55	90	0	55	90	0	50	90	0	55	90	0	50	90	0	60	90	0	55	90
2 - extension	PIP 4	0	70	90	0	70	90	0	70	90	0	70	90	0	65	90	0	70	90	0	70	90	0	65	90	0	70	90	0	65	90
3 - flexion	PIP 5																														

(ap5-1.xls)

(105)

		22/6						23/6						24/6						25/6						26/6					
	TIME	12.30	*(before)*		13.00	*(after)*		12.30	*(before)*		13.20	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 3	0	55	90	0	60	90	0	55	90	0	55	90	0	60	90	0	55	90	0	55	90	0	55	90	0	55	90	0	55	90
2 - extension	PIP 4	0	70	90	0	70	90	0	70	90	0	65	90	0	65	90	0	60	90	0	70	90	0	70	90	0	70	90	0	65	90
3 - flexion	PIP 5																														

(131)

		30/6					
	TIME	time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 3	0	55	90	0	55	90
2 - extension	PIP 4	0	65	90	0	60	90
3 - flexion	PIP 5						

Patient: Ma (#13) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT** (27)

		30/5						31/5						1/6						2/6						3/6					
	TIME	time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 2	0	0	40	0	0	40	0	0	35	0	0	40	0	0	35	0	0	50	0	0	40	0	0	50	0	0	30	0	0	50
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	30	0	0	35	0	0	25	0	0	35	0	0	25	0	0	35	0	0	35	0	0	30	0	0	25	0	0	35
	PIP 5	0	0	30	0	0	35	0	0	25	0	0	35	0	0	30	0	0	45	0	0	30	0	0	35	0	0	30	0	0	35

(27) (53)

		6/6						8/6						9/6						10/6						13/6					
	TIME	time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 2	0	0	45	0	0	55	0	0	45	0	0	55	0	0	40	0	0	50	0	0	40	0	0	50	0	0	45	0	0	55
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	30	0	0	30	0	0	30	0	0	40	0	0	35	0	0	30	0	0	25	0	0	30	0	0	30	0	0	30
	PIP 5	0	0	30	0	0	40	0	0	30	0	0	40	0	0	35	0	0	35	0	0	30	0	0	40	0	0	40	0	0	35

(53) (79)

		14/6						15/6						17/6						20/6						21/6					
	TIME	time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 2	0	0	45	0	0	50	0	0	45	0	0	55	0	0	45	0	0	60	0	0	50	0	0	60	0	0	50	0	0	60
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	30	0	0	30	0	0	30	0	0	30	0	0	25	0	0	30	0	0	30	0	0	30	0	0	20	0	0	30
	PIP 5	0	0	30	0	0	35	0	0	35	0	0	35	0	0	35	0	0	40	0	0	35	0	0	40	0	0	35	0	0	40

(79) (105)

		22/6						23/6						24/6						27/6						29/6					
	TIME	time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - neutral	PIP 2	0	0	50	0	0	55	0	0	50	0	0	60	0	0	45	0	0	55	0	0	45	0	0	50	0	0	45	0	0	50
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	30	0	0	35	0	0	30	0	0	30	0	0	25	0	0	30	0	0	25	0	0	30	0	0	30	0	0	30
	PIP 5	0	0	35	0	0	40	0	0	35	0	0	40	0	0	35	0	0	45	0	0	35	0	0	40	0	0	30	0	0	35

(ap5-1.xls)

(105) (131)

	TIME	30/6 time	(before)		time	(after)		4/7 time	(before)		time	(after)		6/7 time	(before)		time	(after)		7/7 time	(before)		time	(after)		11/7 time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 2	0	0	50	0	0	60	0	0	45	0	0	55	0	0	45	0	0	55	0	0	45	0	0	55	0	0	45	0	0	55
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	30	0	0	35	0	0	25	0	0	30	0	0	25	0	0	25	0	0	25	0	0	30	0	0	25	0	0	25
	PIP 5	0	0	35	0	0	40	0	0	35	0	0	35	0	0	30	0	0	40	0	0	30	0	0	40	0	0	30	0	0	40

		13/7 time	(before)		time	(after)		14/7 time	(before)		time	(after)		18/7 time	(before)		time	(after)		20/7 time	(before)		time	(after)		21/7 time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 2	0	0	45	0	0	55	0	0	45	0	0	60	0	0	50	0	0	55	0	0	50	0	0	55	0	0	45	0	0	60
2 - extension	PIP 3																														
3 - flexion	PIP 4	0	0	25	0	0	25	0	0	20	0	0	30	0	0	20	0	0	30	0	0	20	0	0	20	0	0	25	0	0	28
	PIP 5	0	0	30	0	0	35	0	0	30	0	0	40	0	0	30	0	0	40	0	0	30	0	0	40	0	0	30	0	0	42

		25/7 time	(before)		time	(after)	
		1	2	3	1	2	3
1 - neutral	PIP 2	0	0	45	0	0	58
2 - extension	PIP 3						
3 - flexion	PIP 4	0	0	20	0	0	25
	PIP 5	0	0	30	0	0	40

Patient: OH (#14) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT**

	TIME	date			20/6 time	(before)		time	(after)		21/6 time	(before)		time	(after)		22/6 time	(before)		time	(after)		23/6 time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2				-20	0	70	-20	0	80	-20	0	80	-15	0	80	-15	0	80	-15	0	80	-10	0	80	0	0	85
2 - neutral	MCP 3				-20	0	70	-20	0	75	-20	0	70	-15	0	75	-15	0	80	-15	0	80	-10	0	80	0	0	90
3 - flexion	MCP 4																											
1 - neutral	PIP 2				0	20	50	0	10	50	0	15	45	0	10	50	0	10	50	0	10	55	0	10	45	0	10	60
2 - extension	PIP 3				0	25	60	0	15	70	0	20	60	0	20	70	0	20	65	0	20	70	0	20	60	0	15	75
3 - flexion	PIP 4																											

(27)

	TIME	24/6 time	(before)		time	(after)		27/6 time	(before)		time	(after)		28/6 time	(before)		time	(after)		29/6 time	(before)		time	(after)		30/6 time	(before)		time	(after)	
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 2	0	0	80	0	0	85	-10	0	85	0	0	90	0	0	80	0	0	82	0	0	75	0	0	85	0	0	85	0	0	85
2 - neutral	MCP 3	0	0	80	0	0	85	0	0	85	-5	0	90	-5	0	80	0·	0	85	0	0	80	0	0	85	0	0	80	0	0	85
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	15	45	0	10	45	0	10	50	0	0	55	0	10	60	0	0	65	0	5	60	0	5	60	0	10	50	0	10	60
2 - extension	PIP 3	0	20	60	0	5	65	0	18	70	0	10	70	0	18	65	0	10	80	0	10	65	0	10	75	0	15	65	0	10	85
3 - flexion	PIP 4																														

(ap5-1.xls)

(53)

		1/7						4/7						5/7						6/7						7/7					
	TIME	time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	85	0	0	90	0	0	80	0	0	90	0	0	80	0	0	90	0	0	80	0	0	90	0	0	90	0	0	92
2 - neutral	MCP 3	0	0	80	0	0	90	0	0	85	0	0	90	0	0	85	0	0	95	0	0	85	0	0	90	0	0	90	0	0	92
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	10	60	0	0	65	0	10	50	0	5	60	0	5	60	0	5	65	0	5	60	0	0	65	0	10	55	0	0	63
2 - extension	PIP 3	0	10	70	0	10	80	0	10	70	0	10	65	0	15	65	0	10	65	0	15	65	0	10	70	0	10	80	0	5	80
3 - flexion	PIP 4																														

(79)

		8/7						11/7						12/7						13/7						14/7					
	TIME	time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2 •	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	90	0	0	90	0	0	85	0	0	95	0	0	82	0	0	90	0	0	80	0	0	90	0	0	85	0	0	95
2 - neutral	MCP 3	0	0	90	0	0	90	0	0	85	0	0	95	0	0	90	0	0	90	0	0	90	0	0	92	0	0	85	0	0	95
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	0	55	0	0	60	0	0	60	0	0	60	0	0	65	0	0	60	0	0	50	0	0	60	0	0	58	0	0	65
2 - *extension*	PIP 3	0	10	80	0	10	80	0	5	70	0	5	78	0	5	70	0	5	80	0	10	70	0	10	80	0	10	70	0	10	80
3 - flexion	PIP 4																														

(105)

		15/7						18/7						19/7						20/7						21/7					
	TIME	time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	85	0	0	90	0	0	90	0	0	95	0	0	90	0	0	92	0	0	85	0	0	90	0	0	90	0	0	90
2 - neutral	MCP 3	0	0	85	0	0	90	0	0	90	0	0	95	0	0	90	0	0	90	0	0	92	0	0	90	0	0	92	0	0	98
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	0	55	0	0	65	0	0	50	0	0	65	0	0	55	0	0	62	0	0	50	0	0	55	0	0	60	0	0	70
2 - extension	PIP 3	0	10	70	0	10	75	0	10	75	0	10	75	0	10	70	0	10	78	0	10	70	0	10	75	0	10	75	0	10	80
3 - flexion	PIP 4																														

(131)

		22/7						25/7						26/7						27/7						1/8					
	TIME	time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*			time *(before)*			time *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	85	0	0	92	0	0	90	0	0	95	0	0	90	0	0	92	0	0	90	0	0	95						
2 - neutral	MCP 3	0	0	90	0	0	90	0	0	90	0	0	95	0	0	90	0	0	95	0	0	90	0	0	95						
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	0	74	0	0	70	0	0	50	0	0	54	0	0	60	0	0	60	0	0	50	0	0	60	0	0	55	0	0	65
2 - extension	PIP 3	0	10	82	0	10	80	0	10	75	0	10	75	0	10	75	0	10	80	0	0	75	0	10	80	0	0	70	0	0	85
3 - flexion	PIP 4																														

(ap5-1.xls)

(157)

	TIME	2/8 time (before) 1	2	3	time (after) 1	2	3	3/8 time (before) 1	2	3	time (after) 1	2	3	4/8 time (before) 1	2	3	time (after) 1	2	3	5/8 time (before) 1	2	3	time (after) 1	2	3	8/8 time (before) 1	2	3	time (after) 1	2	3
1 - extension	MCP 2																														
2 - neutral	MCP 3																														
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	0	45	0	0	65	0	0	45	0	0	60	0	0	55	0	0	65	0	0	50	0	0	60	0	0	50	0	0	60
2 - extension	PIP 3	0	0	70	0	0	80	0	0	70	0	0	85	0	0	75	0	0	80	0	0	65	0	0	80	0	0	70	0	0	75
3 - flexion	PIP 4																														

(183)

	TIME	9/8 time (before) 1	2	3	time (after) 1	2	3	10/8 time (before) 1	2	3	time (after) 1	2	3	11/8 time (before) 1	2	3	time (after) 1	2	3	12/8 time (before) 1	2	3	time (after) 1	2	3	16/8 time (before) 1	2	3	time (after) 1	2	3
1 - extension	MCP 2																														
2 - neutral	MCP 3																														
3 - flexion	MCP 4																														
1 - neutral	PIP 2	0	0	50	0	0	60	0	0	50	0	0	60	0	0	50	0	0	60	0	0	45	0	0	60	0	0	45	0	0	70
2 - extension	PIP 3	0	0	70	0	0	75	0	0	75	0	0	75	0	0	70	0	0	80	0	0	65	0	0	75	0	0	60	0	0	80
3 - flexion	PIP 4																														

(209)

	TIME	17/8 time (before) 1	2	3	time (after) 1	2	3	18/8 time (before) 1	2	3	time (after) 1	2	3
1 - extension	MCP 2												
2 - neutral	MCP 3												
3 - flexion	MCP 4												
1 - neutral	PIP 2	0	0	45	0	0	55	0	0	45	0	0	65
2 - extension	PIP 3	0	0	75	0	0	80	0	0	65	0	0	75
3 - flexion	PIP 4												

Patient: ML (#15) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT**

	TIME	date 1	2	3	20/10 time (before) 1	2	3	time (after) 1	2	3	24/10 time (before) 1	2	3	time (after) 1	2	3	27/10 time (before) 1	2	3	time (after) 1	2	3	28/10 time (before) 1	2	3	time (after) 1	2	3
1 - neutral	PIP 3																											
2 - extension	PIP 4																											
3 - flexion	PIP 5				0	30	80	0	20	80	0	30	80	0	20	85	0	30	80	0	15	90	0	30	80	0	20	80

(27)

	TIME	1/11 time (before) 1	2	3	time (after) 1	2	3	3/11 time (before) 1	2	3	time (after) 1	2	3	4/11 time (before) 1	2	3	time (after) 1	2	3	7/11 time (before) 1	2	3	time (after) 1	2	3	8/11 time (before) 1	2	3	time (after) 1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4																														
3 - flexion	PIP 5	0	20	90	0	20	95	0	40	80	0	30	85	0	45	90	0	25	90	0	30	90	0	30	90	0	30	80	0	30	90

(ap5-1.xls)

(53)

		9/11						11/11						14/11						15/11						17/11					
	TIME	time (before)			time (after)			time (before)			time (after)			time (before)			time (after)			time (before)			time (after)			time (before)			time (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4																														
3 - flexion	PIP 5	0	30	90	0	25	95	0	30	90	0	25	95	0	30	90	0	15	90	0	28	92	0	15	92	0	30	90	0	20	92

(79)

		date						21/11						22/11						23/11						24/11					
	TIME	time (before)			time (after)			time (before)			time (after)			time (before)			time (after)			time (before)			time (after)			time (before)			time (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																														
2 - extension	PIP 4																														
3 - flexion	PIP 5	0	30	96	0	20	98	0	28	106	0	15	105	0	30	105	0	18	105	0	25	100	0	15	100	0	30	98	0	15	105

(105)

		28/11						29/11						30/11						11/2 /94					
	TIME	time (before)			time (after)			time (before)			time (after)			time (before)			time (after)			time (before)			time (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - neutral	PIP 3																								
2 - extension	PIP 4																								
3 - flexion	PIP 5	0	30	100	0	20	100	0	30	95	0	20	100	0	25	90	0	15	95	0	30	90	0	15	95

Patient :UK (#16) **ORIGINAL DATA : RANGES OF FINGER JOINT MOVEMENT**

					10/1						13/1						14/1						15/1					
	TIME				09.30 (before)			09.50 (after)			09.30 (before)			11.00 (after)			09.10 (before)			11.00 (after)			09.15 (before)			11.00 (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 3																											
2 - neutral	MCP 4				0	0	60	0	0	65	0	0	60	0	0	65	0	0	60	10	0	65	0	0	60	15	0	70
3 - flexion	MCP5				20	0	40	20	0	50	20	0	40	5	0	55	20	0	40	0	0	55	20	0	40	0	0	70
1 - neutral	PIP 3																											
2 - extension	PIP 4				0	20	80	0	20	85	0	20	80	0	15	85	0	20	80	0	15	90	0	20	80	0	20	80
3 - flexion	PIP 5				0	20	80	0	20	80	0	20	80	0	20	90	0	20	80	0	15	90	0	20	75	0	20	80

(40)

		16/1						17/1						22/1						23/1						24/1					
	TIME	09.20 (before)			11.00 (after)			09.20 (before)			11.00 (after)			09.20 (before)			11.00 (after)			09.20 (before)			11.00 (after)			09.20 (before)			11.00 (after)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1 - extension	MCP 3																														
2 - neutral	MCP 4	0	0	60	0	0	80	0	0	70	0	0	70	0	0	70	0	0	75	0	0	70	0	0	75	0	0	70	0	0	65
3 - flexion	MCP5	20	0	40	10	0	70	10	0	50	10	0	60	20	0	50	15	0	65	20	0	50	20	0	65	20	0	40	20	0	55
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	20	80	0	15	90	0	20	75	0	20	95	0	20	95	0	15	95	0	20	85	0	20	95	0	15	90	0	15	95
3 - flexion	PIP 5	0	20	80	0	15	90	0	20	85	0	20	90	0	20	80	0	15	90	0	20	70	0	20	85	0	20	70	0	20	80

(ap5-1.xls)

(79)

		27/1						29/1						30/1						31/1						3/2					
	TIME	09.30	*(before)*		11.00	*(after)*		09.20	*(before)*		11.00	*(after)*		09.25	*(before)*		11.05	*(after)*		09.25	*(before)*		11.00	*(after)*		09.15	*(before)*		11.15	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 3																														
2 - neutral	MCP 4	0	0	75	0	0	80	0	0	75	0	0	75	0	0	70	0	0	75	0	0	75	0	0	75	0	0	70	0	0	75
3 - flexion	MCP5	20	0	45	15	0	65	15	0	55	15	0	65	15	0	45	15	0	65	15	0	55	15	0	60	15	0	50	15	0	55
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	20	80	0	20	90	0	15	95	0	15	90	0	20	80	0	20	95	0	20	90	0	20	90	0	20	85	0	20	90
3 - flexion	PIP 5	0	20	70	0	20	80	0	15	80	0	15	80	0	20	75	0	20	85	0	20	90	0	20	90	0	20	85	0	20	85

(118)

		4/2						5/2						7/2						10/2						12/2					
	TIME	09.15	*(before)*		11.15	*(after)*		09.25	*(before)*		11.00	*(after)*		09.15	*(before)*		10.50	*(after)*		09.10	*(before)*		10.55	*(after)*		09.25	*(before)*		11.00	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 3																														
2 - neutral	MCP 4	0	0	70	0	0	85	0	0	70	0	0	75	0	0	75	0	0	75	0	0	70	0	0	75	0	0	70	0	0	80
3 - flexion	MCP5	15	0	50	15	0	65	15	0	50	15	0	65	15	0	45	15	0	65	15	0	50	15	0	60	15	0	65	15	0	65
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	15	95	0	20	90	0	15	95	0	20	90	0	15	80	0	15	90	0	15	90	0	10	95	0	10	90	0	10	95
3 - flexion	PIP 5	0	15	80	0	20	85	0	15	80	0	15	80	0	15	70	0	15	85	0	15	80	0	10	90	0	10	90	0	10	85

(157)

		13/2						14/2						27/2						28/2						2/3					
	TIME	09.50	*(before)*		11.50	*(after)*		09.15	*(before)*		11.00	*(after)*		09.30	*(before)*		11.10	*(after)*		09.25	*(before)*		11.00	*(after)*		09.30	*(before)*		11.15	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 3																														
2 - neutral	MCP 4	0	0	70	0	0	75	0	0	65	0	0	70	0	0	70	5	0	75	0	0	70	0	0	75	0	0	75	0	0	75
3 - flexion	MCP5	15	0	50	15	0	55	15	0	40	15	0	50	20	0	50	15	0	60	10	0	60	15	0	65	10	0	60	10	0	65
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	15	95	0	10	95	0	10	90	0	10	90	0	15	90	0	15	90	0	20	90	0	20	95	0	15	95	0	10	95
3 - flexion	PIP 5	0	10	80	0	10	85	0	15	75	0	10	85	0	15	80	0	15	85	0	20	90	0	20	80	0	15	90	0	15	90

(196)

		9/3						11/3						12/3						16/3						17/3					
	TIME	09.25	*(before)*		11.10	*(after)*		09.55	*(before)*		11.00	*(after)*		09.00	*(before)*		10.40	*(after)*		09.00	*(before)*		11.00	*(after)*		09.20	*(before)*		11.55	*(after)*	
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
1 - extension	MCP 3																														
2 - neutral	MCP 4	10	0	75	15	0	75	5	0	80	5	0	80	0	0	75	0	0	80	5	0	75	5	0	75	5	0	70	10	0	75
3 - flexion	MCP5	15	0	50	25	0	60	15	0	55	15	0	60	10	0	60	10	0	65	20	0	60	20	0	65	15	0	50	15	0	65
1 - neutral	PIP 3																														
2 - extension	PIP 4	0	10	90	0	15	95	0	15	95	0	15	90	0	10	90	0	10	100	0	10	95	0	15	90	0	15	90	0	10	90
3 - flexion	PIP 5	0	15	85	0	15	85	0	20	90	0	15	85	0	10	90	0	20	90	0	20	90	0	20	95	0	20	90	0	10	90

(ap5-1 xls)

(235)

		19/3						23/3					
	TIME	09.30	*(before)*		11.05	*(after)*		09.30	*(before)*		11.00	*(after)*	
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 3												
2 - neutral	MCP 4	5	0	75	5	0	85	0	0	75	0	0	75
3 - flexion	MCP5	15	0	60	15	0	70	15	0	60	10	0	65
1 - neutral	PIP 3												
2 - extension	PIP 4	0	10	100	0	5	100	0	10	90	0	10	95
3 - flexion	PIP 5	0	10	90	0	10	80	0	10	80	0	10	85

Patient: Jo (#17) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT**

		date			13/6						14/6						15/6						16/6					
	TIME				time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*		time	*(before)*		time	*(after)*	
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - neutral	PIP 3																											
2 - extension	PIP 4				0	30	60	0	30	65	0	30	60	0	35	60	0	25	55	0	15	55	0	20	55	0	15	60
3 - flexion	PIP 5																											

Patient: HW (#18) **ORIGINAL DATA PROVIDED BY OHH: RANGES OF FINGER JOINT MOVEMENT**

		date			17/12						19/12						20/12						23/12					
	TIME				10.00	*(before)*		11.40	*(after)*		10.40	*(before)*		11.50	*(after)*		11.00	*(before)*		11.55	*(after)*		09.45	*(before)*		11.20	*(after)*	
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2				5	0	75	10	0	70	0	0	70	10	0	65	5	0	70	10	0	70	5	0	75	10	0	65
2 - neutral	MCP 3				10	0	65	10	0	55	5	0	65	10	0	65	10	0	60	10	0	60	10	0	70	10	0	60
3 - flexion	MCP 4				5	0	55	10	0	55	5	0	55	10	0	50	10	0	50	10	0	50	5	0	60	10	0	55
	MCP 5																											
1 - neutral	PIP 2				0	5	90	0	0	90	0	0	90	0	0	90	0	0	90	0	0	90	0	0	105	0	0	105
2 - extension	PIP 3				0	5	90	0	0	95	0	0	90	0	5	90	0	0	90	0	5	90	0	0	95	0	5	95
3 - flexion	PIP 4				0	20	85	0	15	85	0	15	90	0	20	85	0	10	90	0	15	90	0	15	100	0	15	90
	PIP 5																											
1 - neutral	DIP 2				0	0	45	0	0	50	5	0	55	5	0	50	5	0	60	5	0	60	5	0	55	0	0	50
2 - extension	DIP 3				5	0	65	5	0	80	10	0	60	10	0	60	5	0	60	5	0	60	5	0	70	5	0	60
3 - flexion	DIP 4				5	0	40	10	0	45	10	0	40	10	0	45	10	0	40	10	0	45	10	0	45	10	0	45
	DIP 5																											

(27)

		27/12						30/12						2/1						3/1						6/1					
	TIME	10.30	*(before)*		11.30	*(after)*		10.00	*(before)*		11.00	*(after)*		10.00	*(before)*		11.00	*(after)*		09.50	*(before)*		10.50	*(after)*		10.30	*(before)*		11.30	*(after)*	
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	10	0	60	10	0	60	10	0	65	10	0	75	5	0	70	10	0	70	0	10	75	0	0	70	10	0	80	10	0	70
2 - neutral	MCP 3	10	0	60	10	0	60	10	0	65	10	0	65	10	0	70	10	0	65	5	0	70	5	0	70	5	0	70	5	0	65
3 - flexion	MCP 4	10	0	55	10	0	55	10	0	55	10	0	55	10	0	60	10	0	45	5	0	65	5	0	55	5	0	65	10	0	55
	MCP 5																														
1 - neutral	PIP 2	0	0	100	0	0	90	0	0	90	0	0	90	0	0	100	0	0	90	0	0	95	0	0	100	0	0	100	0	0	95
2 - extension	PIP 3	0	5	95	0	5	95	0	5	95	0	5	95	0	5	100	0	5	95	0	5	95	0	5	95	0	5	100	0	5	95
3 - flexion	PIP 4	0	10	95	0	15	90	0	15	90	0	15	95	0	15	95	0	10	90	0	10	95	0	10	95	0	10	95	0	15	90
	PIP 5																														
1 - neutral	DIP 2	5	0	60	5	0	60	5	0	65	5	0	55	5	0	55	5	0	60	5	0	60	5	0	50	5	0	55	5	0	50
2 - extension	DIP 3	5	0	60	5	0	60	5	0	65	5	0	60	5	0	60	5	0	60	5	0	65	5	0	60	5	0	70	0	0	60
3 - flexion	DIP 4	10	0	35	10	0	45	10	0	45	10	0	40	10	0	45	10	0	45	10	0	50	10	0	45	5	0	50	10	0	45
	DIP 5																														

(ap5-1.xls)

(53)

		7/1						8/1						9/1						10/1						13/1					
	TIME	11.25 *(before)*			12.30 *(after)*			10.30 *(before)*			12.10 *(after)*			11.30 *(before)*			12.30 *(after)*			11.05 *(before)*			12.00 *(after)*			11.05 *(before)*			12.05 *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	75	5	0	75	5	0	70	5	0	75	0	0	70	0	0	70	5	0	75	5	0	70	5	0	75	5	0	80
2 - neutral	MCP 3	5	0	75	5	0	75	10	0	70	10	0	75	5	0	70	0	0	70	10	0	70	5	0	70	10	0	75	5	0	75
3 - flexion	MCP 4	5	0	65	10	0	65	10	0	50	10	0	60	5	0	65	5	0	60	10	0	65	10	0	60	10	0	65	10	0	65
	MCP 5																														
1 - neutral	PIP 2	0	0	100	0	5	100	0	5	105	0	0	90	0	5	95	0	0	95	0	5	95	0	5	100	0	5	95	0	0	95
2 - extension	PIP 3	0	0	100	0	5	100	0	15	100	0	5	95	0	5	100	0	5	95	0	5	100	0	5	100	0	0	100	0	0	100
3 - flexion	PIP 4	0	10	95	0	15	95	0	15	95	0	10	90	0	15	95	0	15	90	0	15	95	0	15	90	0	15	95	0	15	95
	PIP 5																														
1 - neutral	DIP 2	10	0	60	5	0	55	5	0	55	0	0	50	5	0	55	5	0	60	5	0	55	5	0	55	5	0	55	5	0	55
2 - extension	DIP 3	5	0	65	5	0	65	5	0	65	5	0	55	5	0	60	5	0	60	5	0	65	5	0	60	10	0	65	5	0	65
3 - flexion	DIP 4	10	0	45	10	0	45	5	0	45	10	0	45	5	0	45	5	0	40	5	0	45	10	0	45	10	0	45	10	0	45
	DIP 5																														

(79)

		14/1						15/1						16/1						17/1						21/1					
	TIME	11.20 *(before)*			12.30 *(after)*			12.55 *(before)*			13.50 *(after)*			11.40 *(before)*			12.20 *(after)*			11.20 *(before)*			12.20 *(after)*			11.00 *(before)*			12.00 *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	5	0	75	10	0	70	5	0	80	5	0	70	10	0	75	10	0	70	5	0	70	10	0	75	10	0	75	10	0	80
2 - neutral	MCP 3	10	0	75	10	0	75	10	0	75	10	0	75	10	0	75	10	0	75	10	0	70	10	0	75	10	0	80	10	0	80
3 - flexion	MCP 4	10	0	70	10	0	70	10	0	65	10	0	65	10	0	70	10	0	70	10	0	70	10	0	70	10	0	70	10	0	75
	MCP 5																														
1 - neutral	PIP 2	0	5	95	0	5	105	0	0	100	0	0	90	0	0	100	0	0	105	0	0	100	0	0	105	0	0	105	0	0	100
2 - extension	PIP 3	0	0	100	0	5	105	0	10	100	0	5	95	0	0	100	0	0	105	0	0	100	0	0	105	0	0	105	0	0	115
3 - flexion	PIP 4	0	15	100	0	15	105	0	15	95	0	10	95	0	10	100	0	10	105	0	15	105	0	15	100	0	15	105	0	10	100
	PIP 5																														
1 - neutral	DIP 2	5	0	55	5	0	55	5	0	55	5	0	55	5	0	60	10	0	55	10	0	60	10	0	55	10	0	60	10	0	60
2 - extension	DIP 3	5	0	65	5	0	65	5	0	65	5	0	60	0	0	65	5	0	60	10	0	70	10	0	65	10	0	70	10	0	70
3 - flexion	DIP 4	10	0	45	10	0	45	10	0	45	10	0	50	5	0	50	10	0	45	10	0	50	15	0	50	10	0	45	10	0	50
	DIP 5																														

(105)

		27/1						28/1						29/1						30/1						31/1					
	TIME	10.30 *(before)*			12.20 *(after)*			10.30 *(before)*			12.05 *(after)*			09.00 *(before)*			10.10 *(after)*			11.15 *(before)*			12.15 *(after)*			11.15 *(before)*			12.35 *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	10	0	85	10	0	80	5	0	85	10	0	80	10	0	80	10	0	70	5	0	80	5	0	75	0	0	80	0	0	85
2 - neutral	MCP 3	10	0	75	10	0	75	10	0	80	0	0	75	0	0	80	0	0	75	10	0	75	10	0	75	5	0	80	10	0	80
3 - flexion	MCP 4	5	0	70	5	0	65	10	0	70	0	0	75	0	0	75	0	0	70	10	0	65	10	0	65	10	0	70	10	0	70
	MCP 5																														
1 - neutral	PIP 2	0	10	110	0	5	100	0	0	105	0	5	105	0	0	95	0	0	100	0	0	100	0	0	105	0	0	100	0	0	100
2 - extension	PIP 3	0	10	110	0	5	100	0	5	105	0	10	105	0	5	100	0	5	100	0	5	100	0	5	100	0	10	105	0	5	100
3 - flexion	PIP 4	0	15	115	0	10	100	0	10	105	0	15	105	0	10	95	0	10	90	0	10	100	0	10	100	0	15	100	0	10	100
	PIP 5																														
1 - neutral	DIP 2	10	0	65	10	0	60	5	0	50	5	0	60	5	0	60	5	0	50	5	0	60	5	0	55	0	0	60	0	0	60
2 - extension	DIP 3	10	0	75	10	0	60	5	0	65	5	0	70	5	0	70	5	0	65	5	0	65	5	0	70	5	0	70	0	0	70
3 - flexion	DIP 4	10	0	50	10	0	50	5	0	50	5	0	50	5	0	50	5	0	50	10	0	45	10	0	50	10	0	55	5	0	60
	DIP 5																														

(ap5-1.xls)

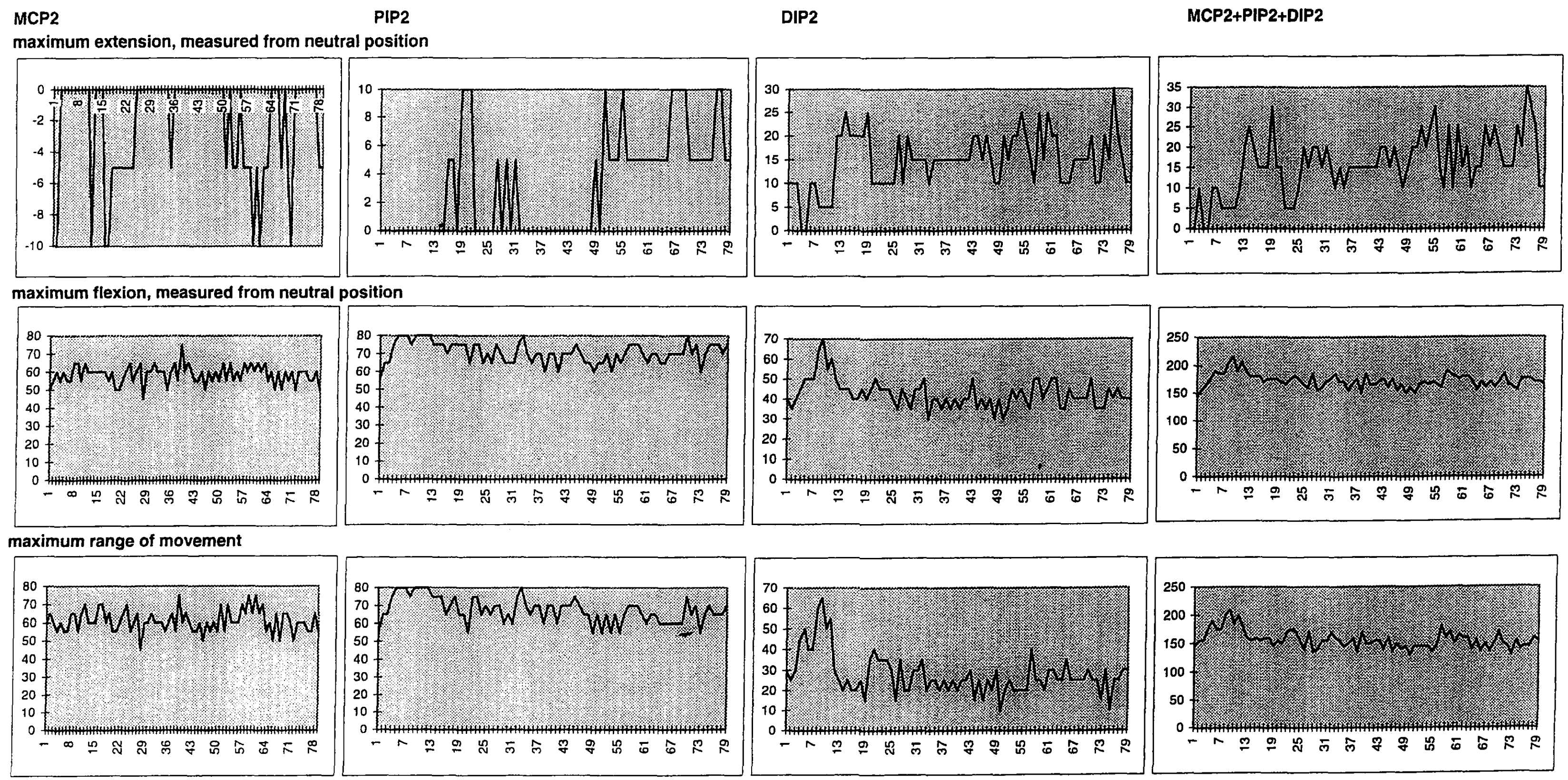
(131)

	TIME	3/2 11.00 *(before)*			12.00 *(after)*			7/2 11.00 *(before)*			12.05 *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	0	0	85	0	0	85	0	0	80	0	0	80
2 - neutral	MCP 3	10	0	80	10	0	80	10	0	80	0	0	80
3 - flexion	MCP 4	10	0	75	10	0	70	10	0	70	10	0	70
	MCP 5												
1 - neutral	PIP 2	0	0	100	0	0	100	0	0	100	0	0	100
2 - extension	PIP 3	0	5	100	0	5	105	0	5	105	0	5	100
3 - flexion	PIP 4	0	10	95	0	10	100	0	10	105	0	10	105
	PIP 5												
1 - neutral	DIP 2	0	0	60	0	0	60	0	0	60	0	0	60
2 - extension	DIP 3	0	0	70	0	0	65	0	0	70	5	0	70
3 - flexion	DIP 4	5	0	50	5	0	50	5	0	50	10	0	45
	DIP 5												

	TIME	10/2 11.00 *(before)*			12.00 *(after)*			11/2 10.45 *(before)*			11.50 *(after)*		
		1	2	*3*	*1*	2	*3*	*1*	2	*3*	*1*	2	*3*
1 - extension	MCP 2	5	0	80	5	0	80	0	0	80	0	0	75
2 - neutral	MCP 3	15	0	80	10	0	80	5	0	80	5	0	75
3 - flexion	MCP 4	15	0	75	10	0	75	10	0	70	10	0	70
	MCP 5												
1 - neutral	PIP 2	0	0	105	0	0	105	0	0	105	0	0	95
2 - extension	PIP 3	0	5	105	0	5	110	0	5	105	0	5	95
3 - flexion	PIP 4	0	5	100	0	10	110	0	10	100	0	10	95
	PIP 5												
1 - neutral	DIP 2	10	0	65	5	0	65	5	0	60	5	0	60
2 - extension	DIP 3	10	0	70	10	0	65	5	0	65	5	0	65
3 - flexion	DIP 4	10	0	50	10	0	50	10	0	45	10	0	45
	DIP 5												

(ap5-1.xls)

Patient: RB (#1)



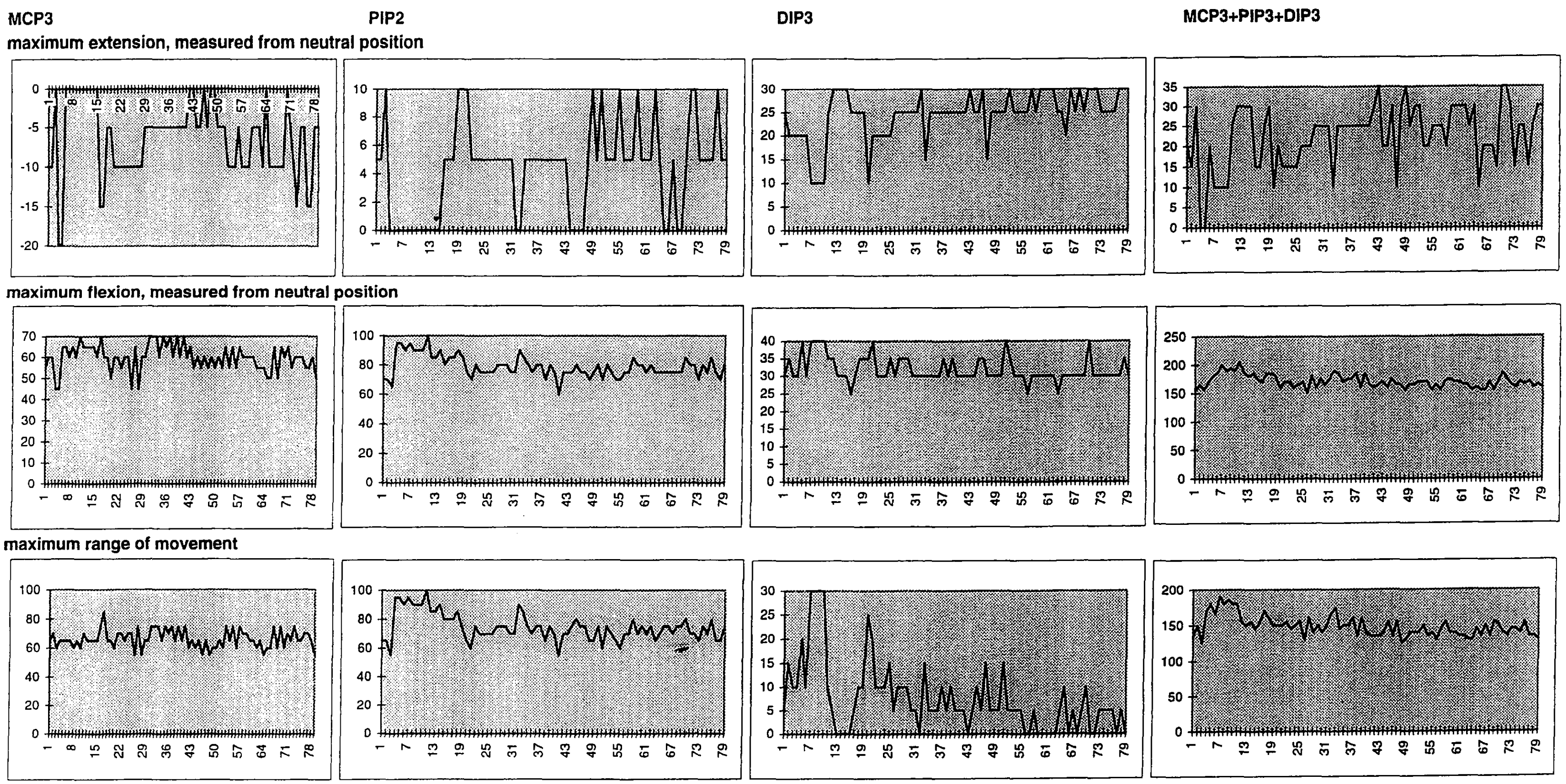
(ap5-2p1.xls from berbartl.xls)

figure A5.2 - 1 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)



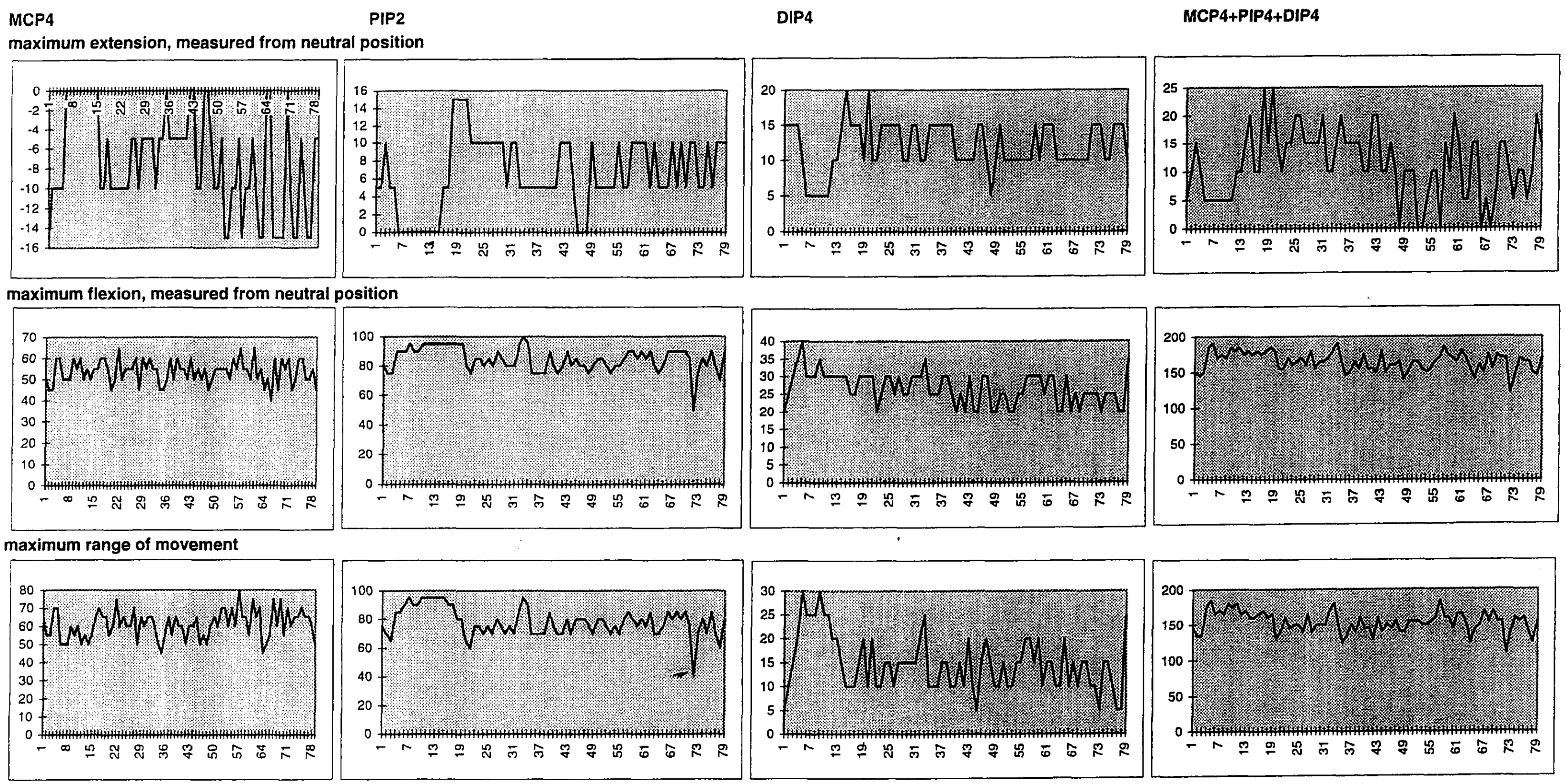
(ap5-2p1.xls from berbartl.xls)

figure A5.2 - 2 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)



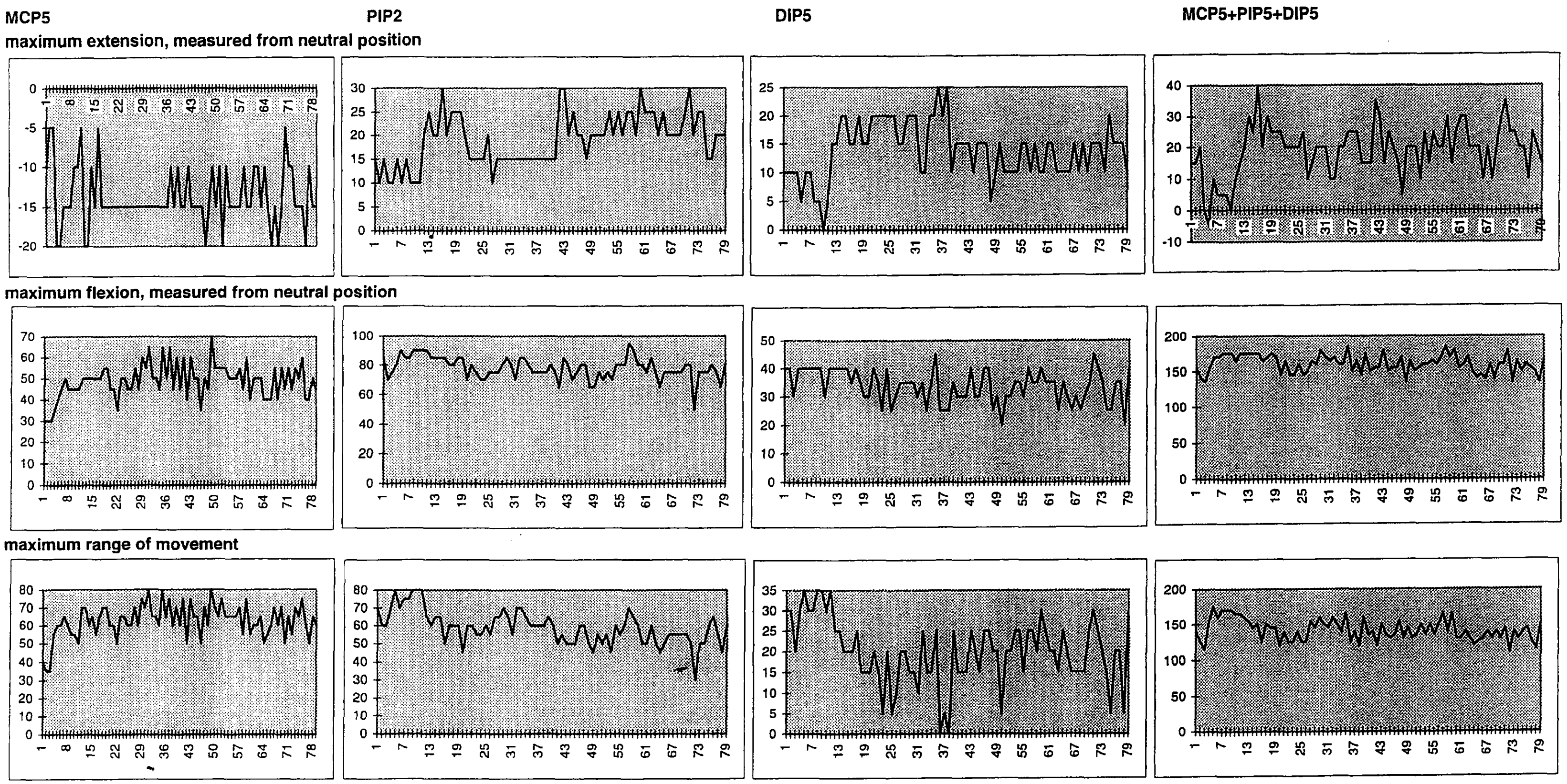
(ap5-2p1.xls from berbartl.xls)

figure A5.2 - 3 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)



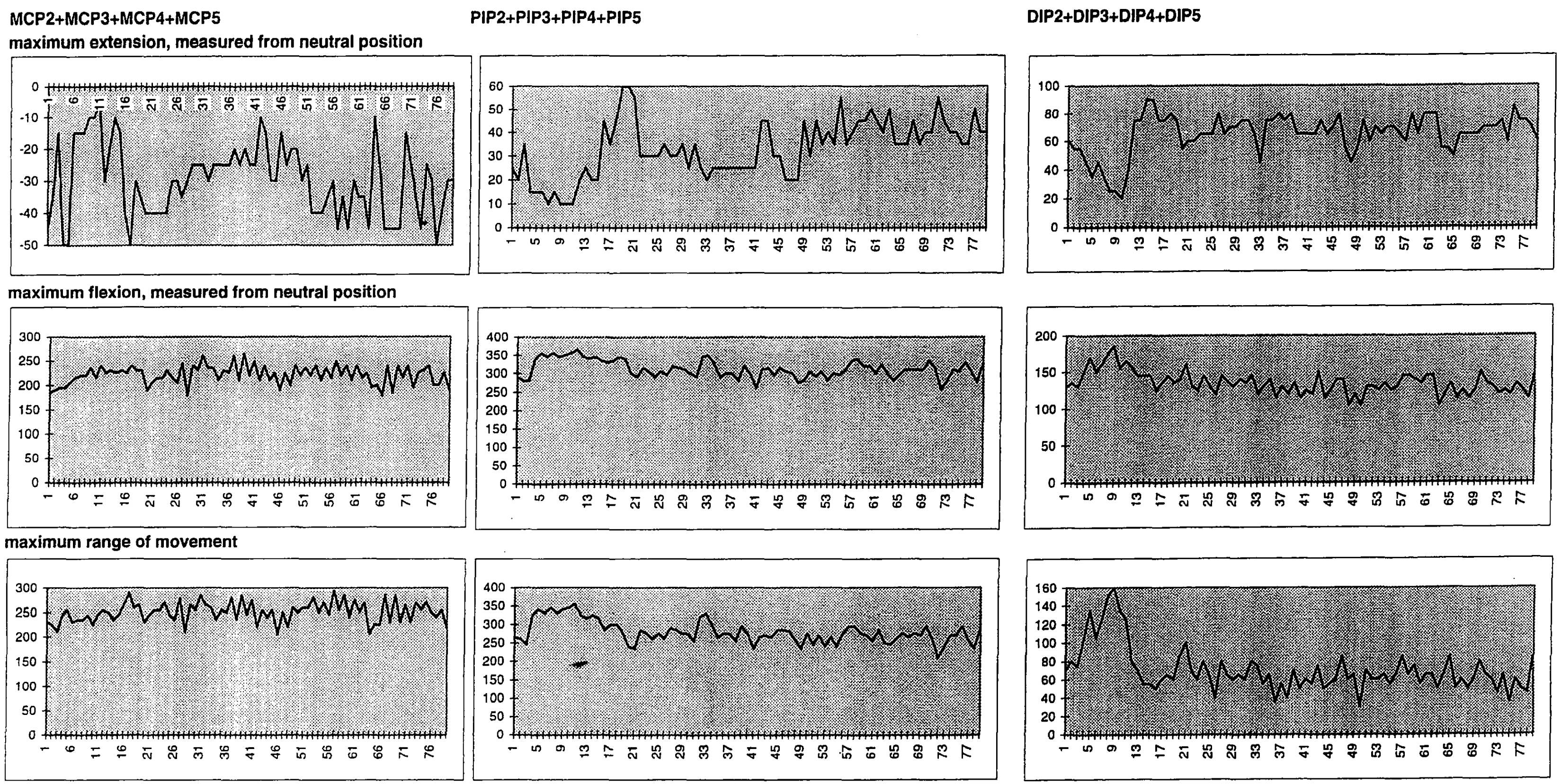
(ap5-2p1.xls from berbartl.xls)

figure A5.2 - 4 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)



(ap5-2p1.xls from berbartl.xls)

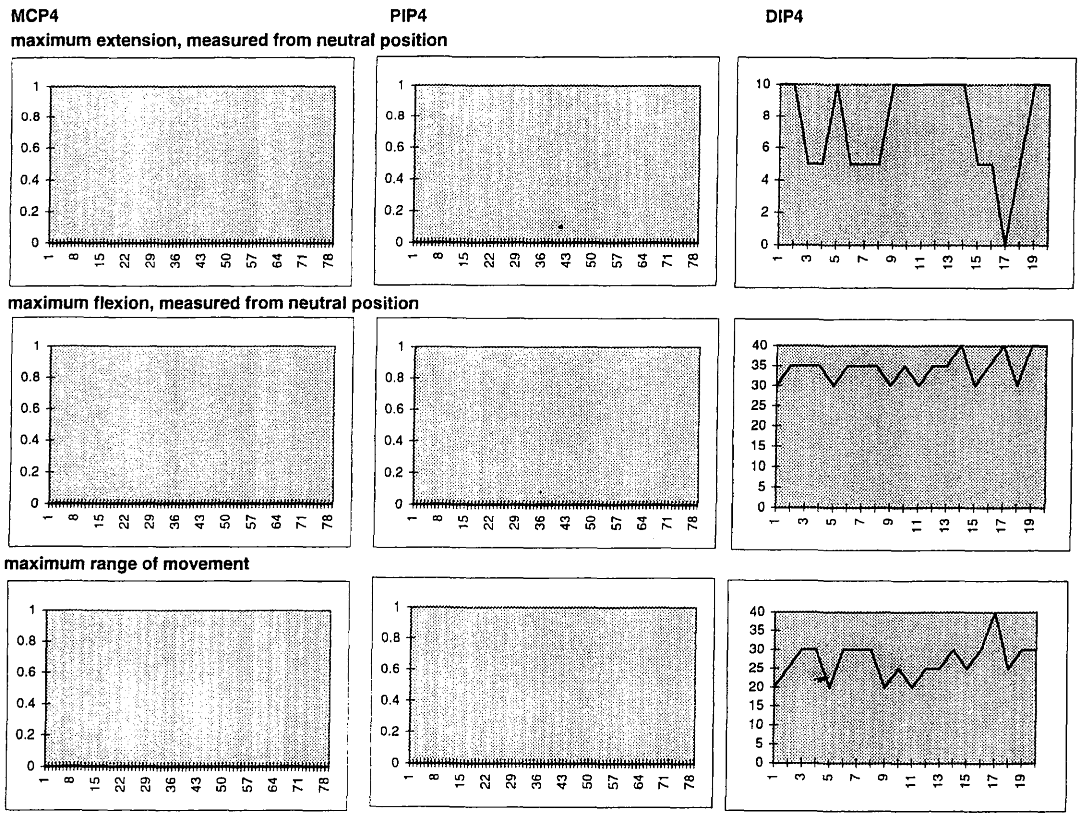
figure A5.2 - 5 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: MK (#3)



(ap5-2p2.xls)

figure A5.2 - 6 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: Z (#4)

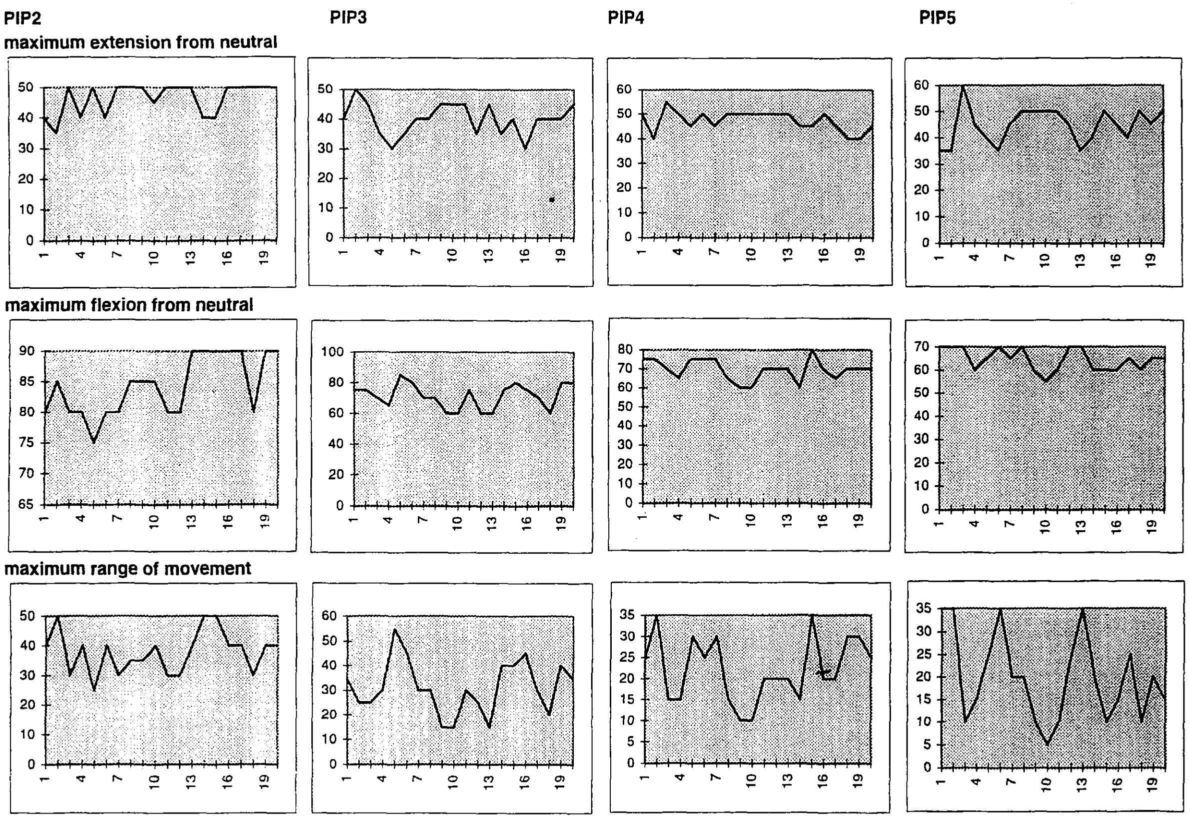


figure A5.2 - 7 (see section 7.2)

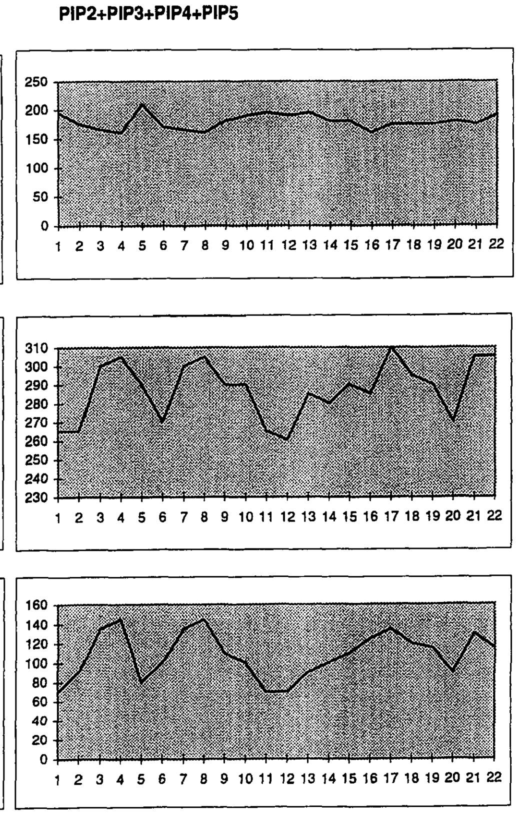


figure A5.2 - 8 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: CDB (#5)

PIP4

maximum extension, measured from neutral position

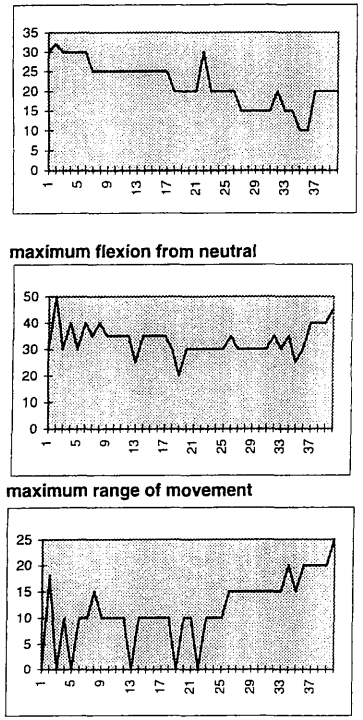


figure A5.2 - 9 (see section 7.2)

Patient: AM (#6)

PIP3 *PIP4*

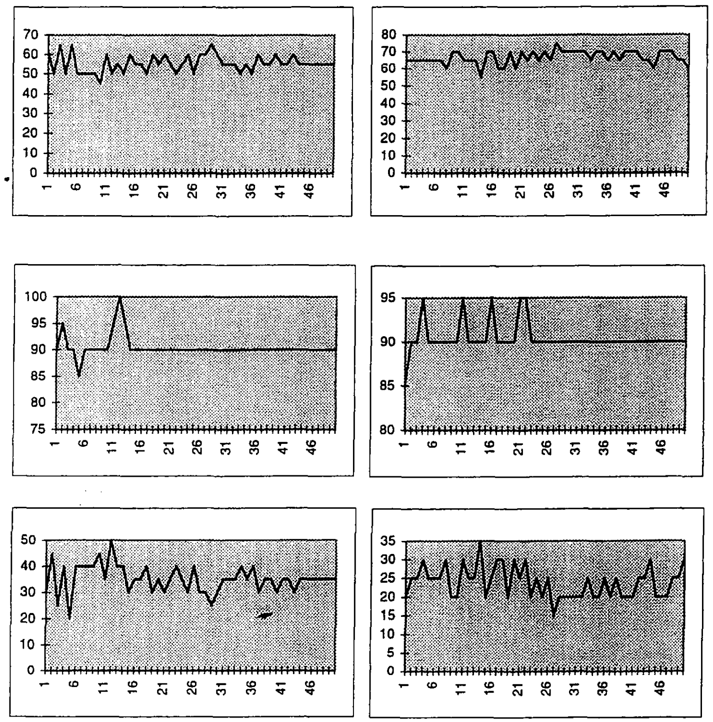


figure A5.2 - 10 (see section 7.2)

(ap5-2p3.xls)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: Ma (#13)

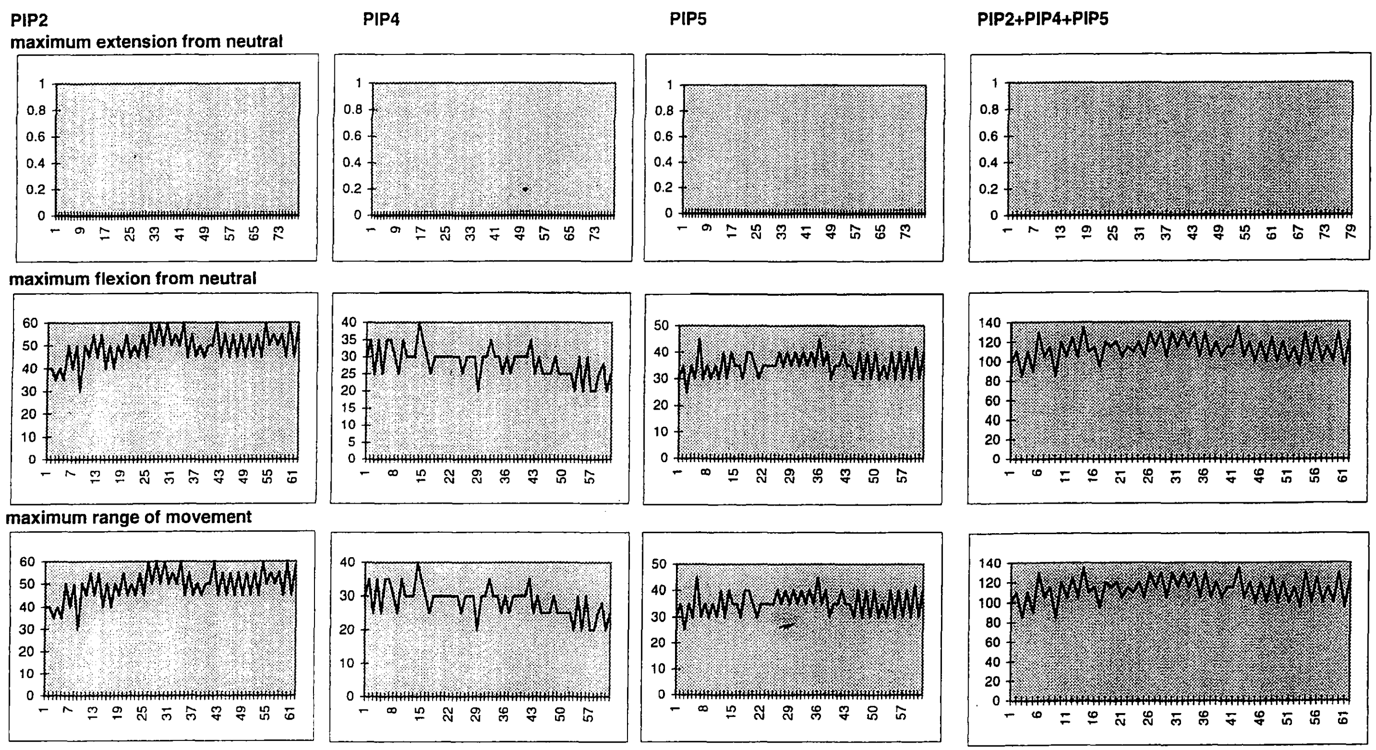


figure A5.2 - 11 (see section 7.2)

(ap5-2p3.xls)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: OH (#14)

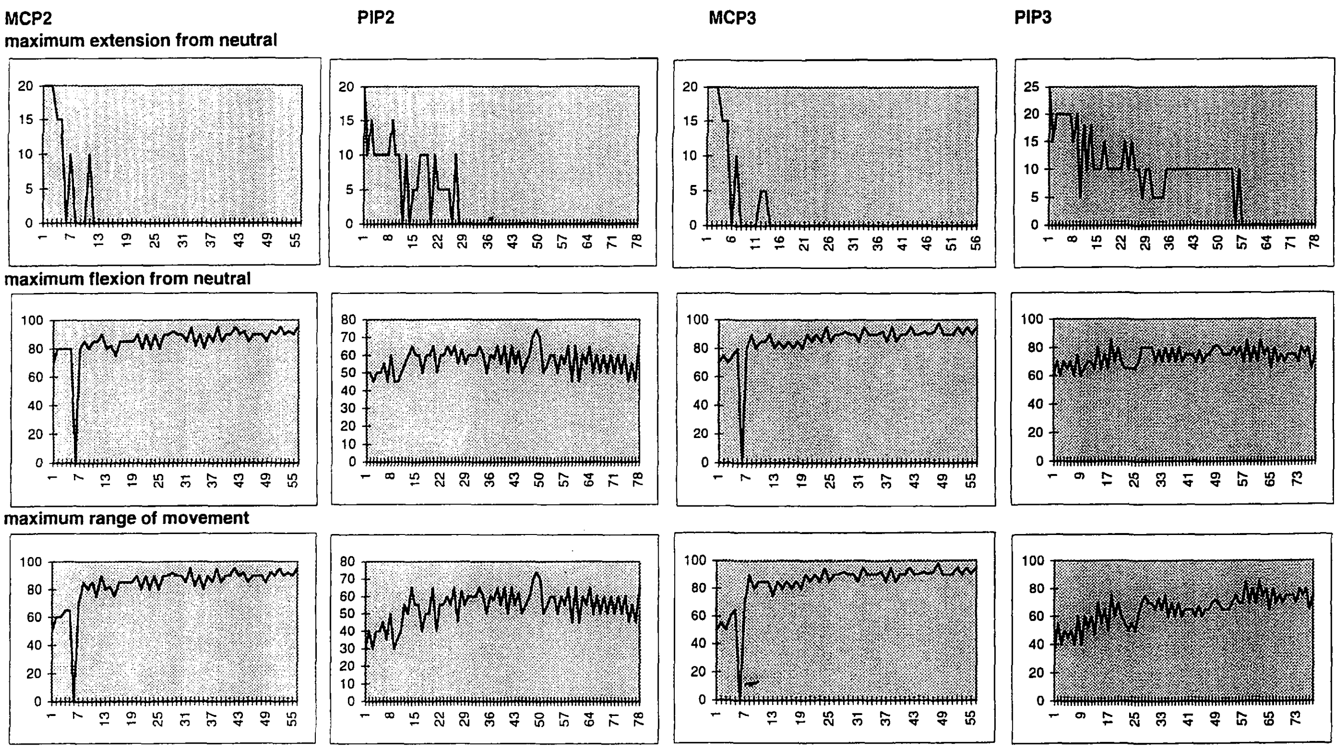


figure A5.2 - 12 (see section 7.2)

(ap5-2p4.xls)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: ML (#15)

PIP5
maximum extension from neutral

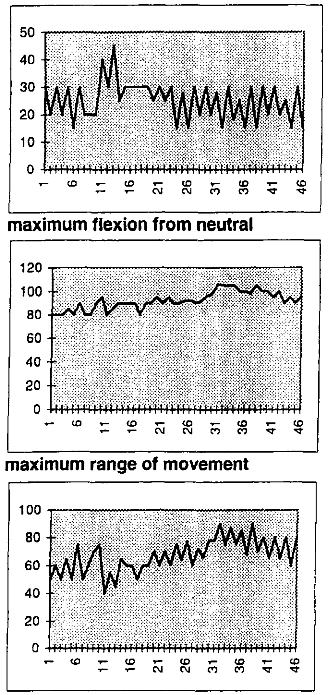


figure A5.2 - 13 (see section 7.2)

Patient: UK (#16)

MCP4 **PIP4** **MCP5** **PIP5**

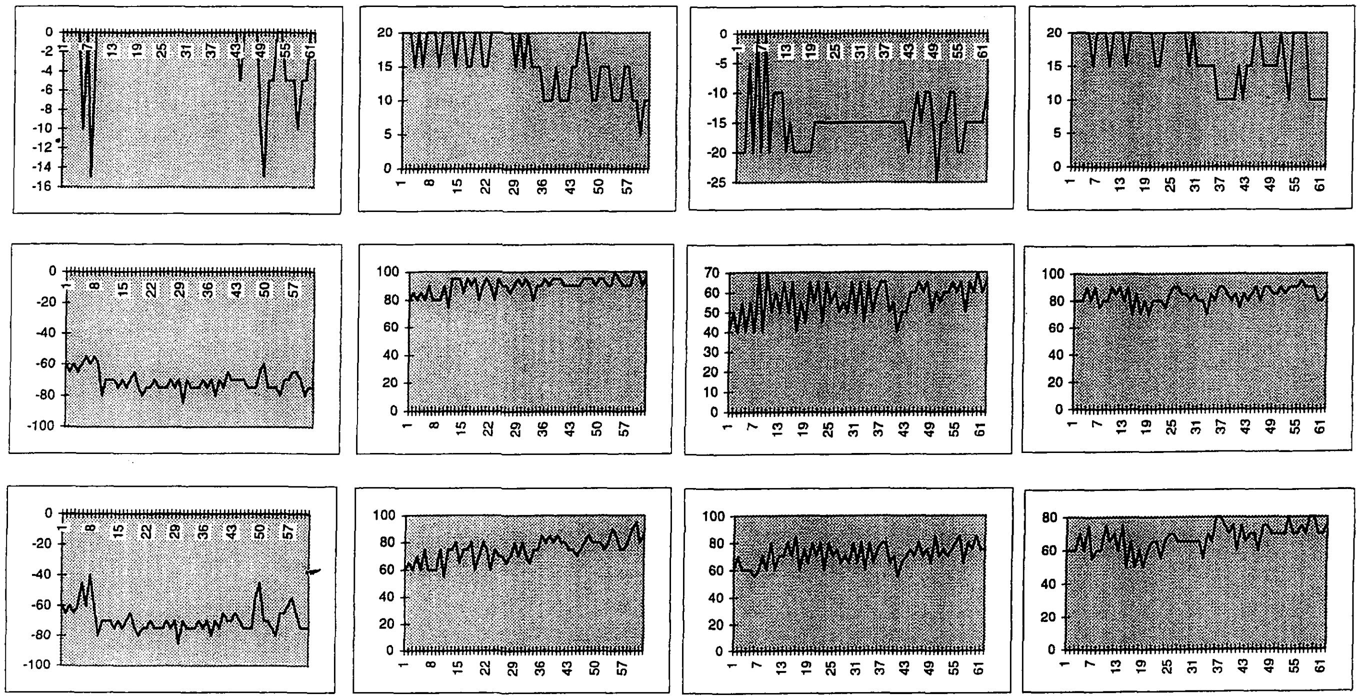


figure A5.2 - 14 (see section 7.2)

(ap5-2p4.xls)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

Patient: Jo (#17)

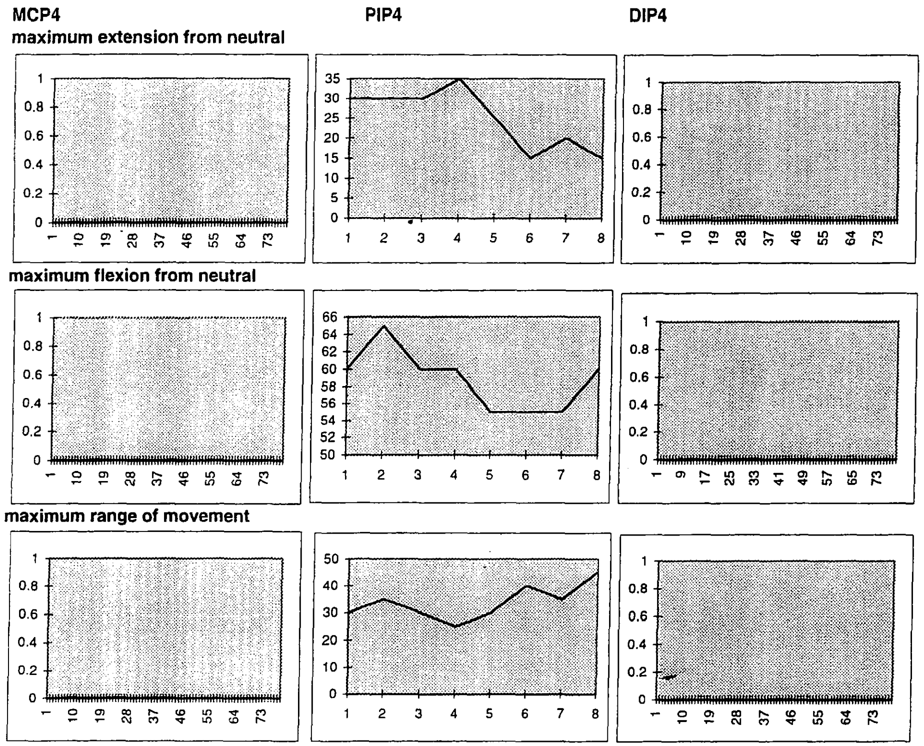


figure A5.2 - 15 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

(ap5-2p5.xls)

Patient: Wi (#18)

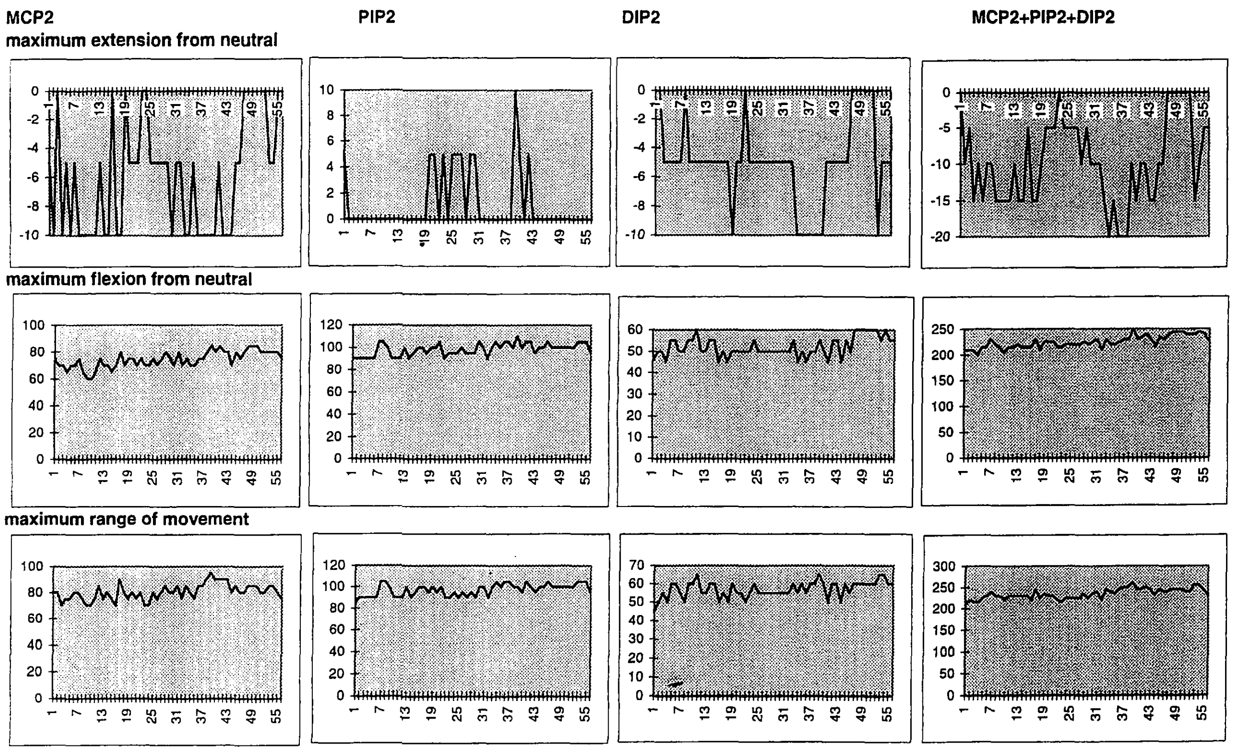


figure A5.2 - 16 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

(ap5-2p5.xls)

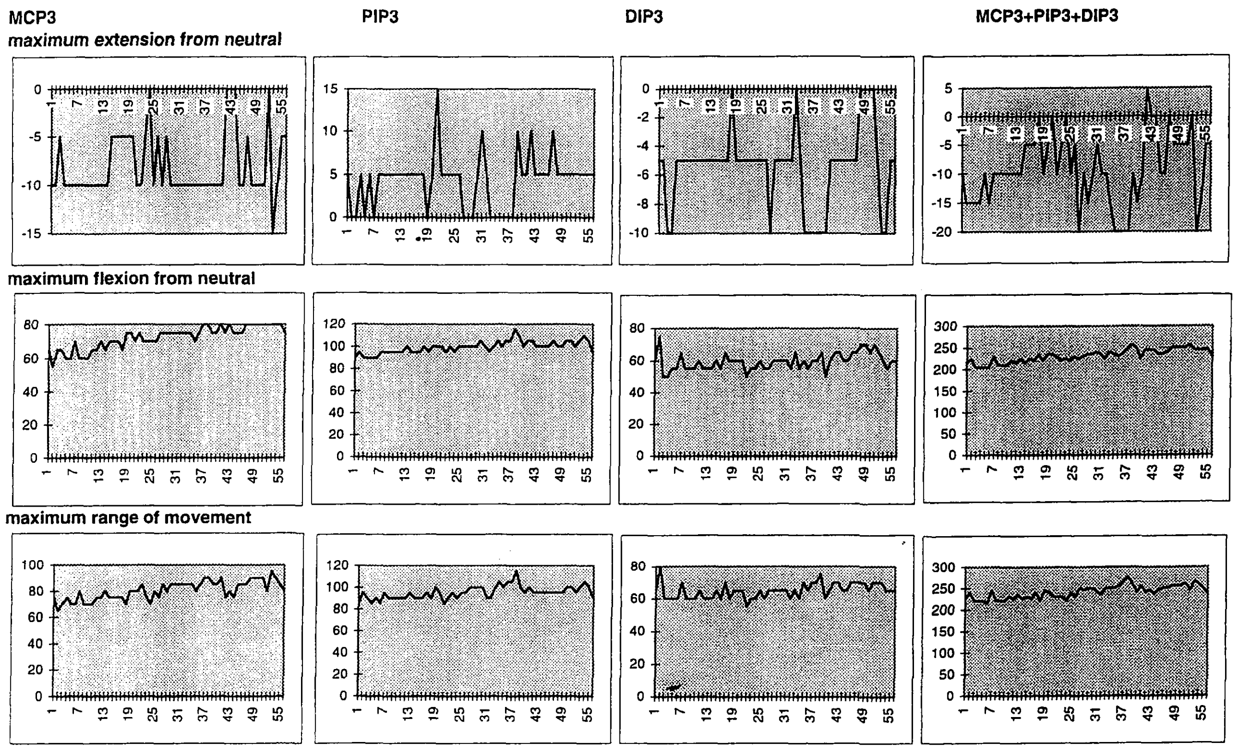


figure A5.2 - 17 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

(ap5-2p5.xls)

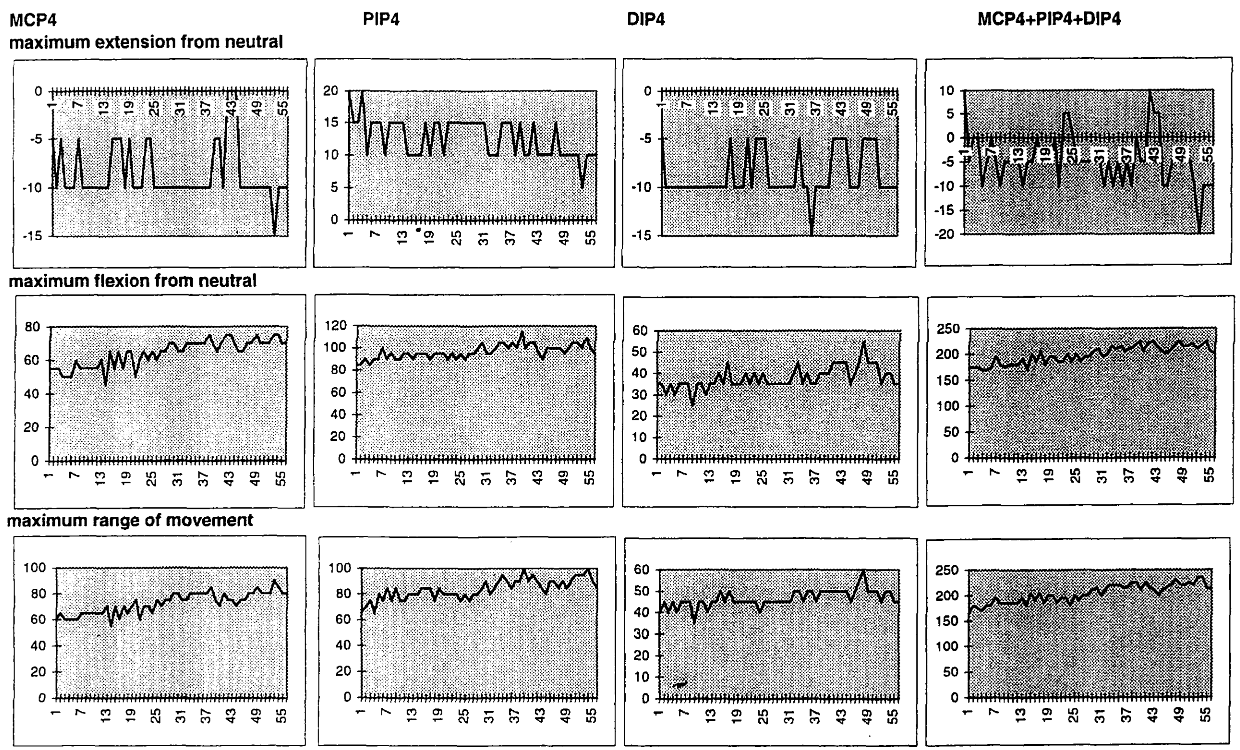


figure A5.2 - 18 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

(ap5-2p5.xls)

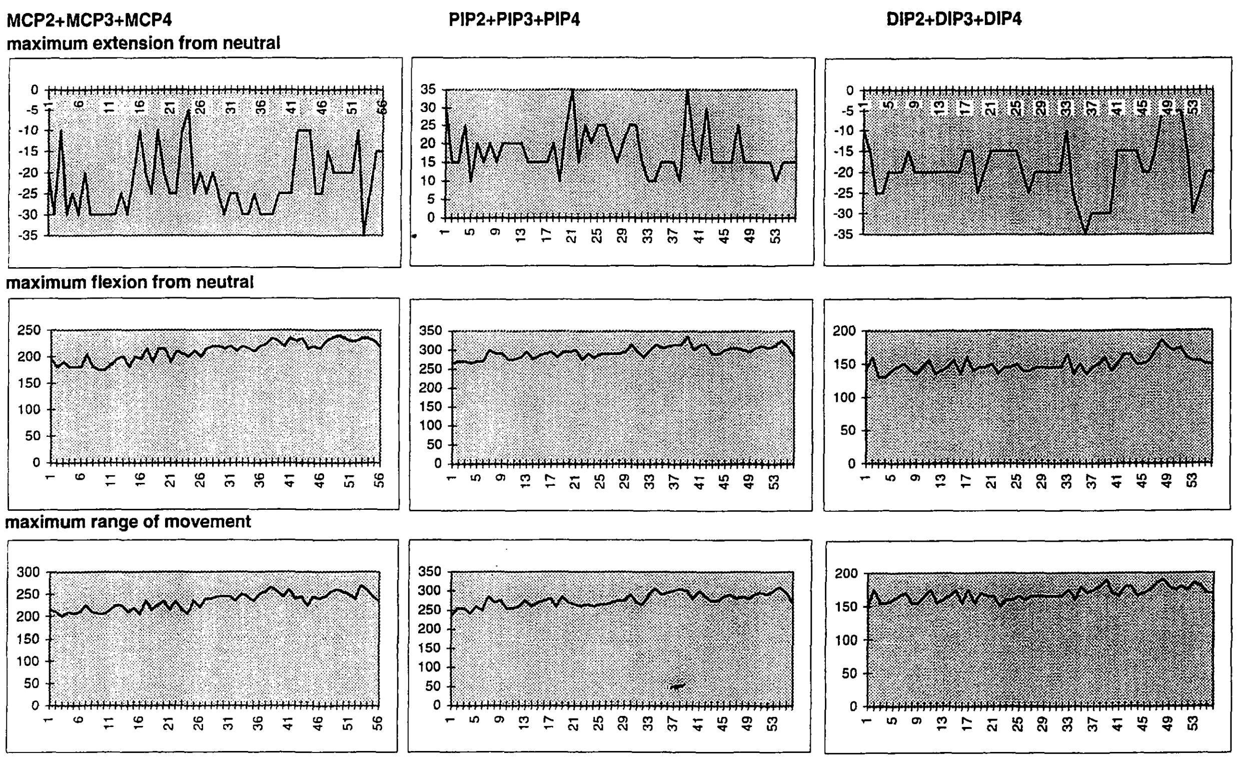


figure A5.2 - 19 (see section 7.2)

y axis: degrees of active movement from neutral position

x axis: joint movement, measured before and after each CPM treatment session

original data in appendix 5.1 (page 356)

(ap5-2p5.xls)

Details of the percentage occurrences of changes in patients' finger joint angles, provided by each CPM treatment session

refer to section 7.2
n = number of visits which provided sets of data

improvement in joint extension (expressed as a percentage)

		- 20^0	- 15^0	- 10^0	- 5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
1 - RB	MCP2			8	5	69	18				
n = 39	MCP3			3	3	77	15	3			
	MCP4		3	3	13	21	31	18	8	5	
	MCP5			5	23	49	21	3			
	PIP2			5	13	82					
	PIP3				26	69	5				
	PIP4			3	23	67	8				
	PIP5				28	54	10	8			
	DIP2		3	3	5	54	26	10			
	DIP3			3	10	64	15	3	5		
	DIP4				13	69	18				
	DIP5			3	23	49	23		3		

table 1 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		- 20^0	- 15^0	- 10^0	- 5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
1 - RB	MCP2			8	3	23	**41**	21	3	3	
n = 39	MCP3			3	5	33	23	26	8	3	
	MCP4		3	3	3	31	36	15	8	3	
	MCP5				5	41	8	15	23	5	3
	PIP2		3	10	18	41	23	5			
	PIP3		3	10	31	38	10	8			
	PIP4.	3		5	21	41	18	5	3	3	3
	PIP5			10	18	44	13	8	5		3
	DIP2	3	5	3	21	26	31	10		3	
	DIP3			3	18	51	21	8			
	DIP4			3	8	54	28	5	3		
	DIP5		3	10	15	33	18	18	10	3	

table 2 - appendix 5.3

example: On 16 out of 39 occasions (i.e. 41%) when patient RB attended for treatment, she obtained a 5 degree increase in MCP2 joint maximum flexion angle after treatment. This is shown in boldtype in the table above.

improvement in joint range of motion (expressed as a percentage)

		-20^0	-15^0	-10^0	-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$
1 - RB	MCP2		3	5	10	23	28	15	13	3	
n = 39	MCP3			5	3	28	21	31	10	3	
	MCP4		3	3	10	21	31	18	8	8	
	MCP5			5	13	18	18	21	13	10	3
	PIP2		3	23	13	33	26	3			
	PIP3		8	15	26	33	10	8			
	PIP4	3	5	5	31	28	10	10	3	3	3
	PIP5			13	23	28	15	13	5	3	
	DIP2	3	3	5	13	31	26	15		5	
	DIP3	3		3	18	38	26	8	3	3	
	DIP4				21	33	33	10	3		
	DIP5		3	13	18	31	18	10	3		5

table 3 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-25^0	-20^0	-15^0	-10^0	-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$
1 - RB	SUM MCP		3		8	21	33	15	15	5		
n = 39	SUM PIP	3	3	13	8	13	41	18	3			
	SUM DIP	3	3		5	8	44	13	8	10	3	5
	ALL 2			5	8	13	38	28	5	3		
	ALL3			5	5	15	54	5	5	5	5	
	ALL 4				3	26	49	18	5			
	ALL 5			8	13	13	36	18	5	5	3	

table 4 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-40^0	-35^0	-30^0	-25^0	-20^0	-15^0	-10^0	-5^0	0^0
1 - RB	SUM MCP		3				3			10
n = 39	SUM PIP	3	3		8	8	3	10	15	10
	SUM DIP	3			3		5	13	18	5
	ALL 2					3	5	8	18	13
	ALL 3							15	26	5
	ALL 4.					3	5	3	10	10
continued	ALL5					3	3	3	13	13

		$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$	$30^0 +$	$35^0 +$	$40^0 +$	$45^0 +$	$50^0 +$	$55^0 +$	$60^0 +$
continued	SUM MCP	13	8	13	8	8	13	8	5			5	5
1 - RB	SUM PIP	15	5	5	3	8			3		3		
n = 39	SUM DIP	0	26	13	5	5	5						
	ALL 2	15	18	13		3	3	3					
	ALL 3	13	15	21		3	3						
	ALL 4	26	13	10	10	8	3						
	ALL5	18	8	13	13	5	10						

table 5 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-40°	-35°	-30°	-25°	-20°	-15°	-10°	-5°	0°
1 - RB	SUM MCP		3		3		3	3	5	3
n = 39	SUM PIP	5	8	5	3	10	5	13	8	5
	SUM DIP						10	13	13	5
	ALL 2					5	10	8	5	21
	ALL 3			3	10	5	3	15	8	10
	ALL4				3	3	5		5	23
continued	ALL 5					3	8	8	8	13

		5° +	10° +	15° +	20° +	25° +	30° +	35° +	40° +	45° +	50° +	55° +	60° +
continued	SUM MCP	5	10	8	15	3	10	8	5	5	5	5	3
1 - RB	SUM PIP	3	8	13	5		5		3		3		
n = 39	SUM DIP	5	21	3	13	3	8		8				
	ALL 2	13	8	21	3		3	5					
	ALL 3	15	15	5		5	3			3			
	ALL4	15	15	8	10	5	8						
	ALL 5	10	10	13	8	8	8	3	3				

table 6 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-5°	0°	5° +	10° +	15° +
3 - MK *n = 10*	PIP4		90	10		

table 7 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-15°	-10°	-5°	0°	5° +	10° +
3 - MK *n = 10*	PIP4		10		30	60	

table 8 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-15°	-10°	-5°	0°	5° +	10° +	15° +
3 - MK *n = 10*	PIP4		10		30	50	10	

table 9 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
4 - GZ	PIP2		9		36	18	36		
n = 11	PIP3		9	18	36		36		
	PIP4			36	36	18	9		
	PIP5			27	27	27	9	9	

table 10 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-20^0	-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
4 - GZ	PIP2			9		55	36			
n = 11	PIP3		9	9	36	36			9	
	PIP4			27	9	55	9			
	PIP5			18	18	36	18	9		

table 11 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-20^0	-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
4 - GZ	PIP2			18		18	18	27	18		
n = 11	PIP3			27	27	18	18				9
	PIP4		18		27	36		18			
	PIP5		18		18	18	18	18	9		

table 12 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +
5 - CDB *n = 20*	PIP4		5	5	85	5	

table 13 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
5 - CDB *n = 20*	PIP4		5	40	30	20	5	

table 14 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
5 - CDB *n = 20*	PIP4		5		45	25	20		5	

table 15 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-10^0	-5^0	0^0	5^0+	10^0+	15^0+	20^0+
6 - AM	PIP3		8	32	40	12	8	
n = 25	PIP4		4	48	44	4		

table 16 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-10^0	-5^0	0^0	5^0+	10^0+
6 - AM	PIP3		4	84	12	
n = 25	PIP4		4	84	12	

table 17 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-10^0	-5^0	0^0	5^0+	10^0+	15^0+	20^0+	25^0+
6 - AM	PIP3		8	32	40	4	12	4	
n = 25	PIP4		8	28	56	8			

table 18 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0+	10^0+	15^0+	20^0+	25^0+	30^0+	45^0+
7 - CM	PIP2	7		7	40	20	13		13			
n = 15	PIP3			7	27	27	13	7	13			7
	PIP4		7		40	27	13	13				
	PIP5				33	20	33	7		7		

table 19 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0+	10^0+	15^0+
7 - CM	PIP2		20	20	40	7	13	
n = 15	PIP3			33	47	13	7	
	PIP4		13	27	40	7	13	
	PIP5		13	33	27	20		

table 20 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-25^0	-20^0	-15^0	-10^0	-5^0	0^0	5^0+	10^0+	15^0+	20^0+	25^0+	40^0+
7 - CM	PIP2				13	13	47		7		20		
n = 15	PIP3					20	13	7	33	7	13		7
	PIP4	7		7	7	13	20	13	7	27			
	PIP5		7	7	7	7	13	20	27	13			

table 21 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-5^0	0^0	5^0 +	10^0 +
13 - Ma	PIP2		100		
n = 31	PIP4		100		
	PIP5		100		

table 22 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
13 - Ma	PIP2			3	23	55	16	3	
n = 31	PIP4		6	35	35	23			
	PIP5		3	10	42	42	3		

table 23 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
13 - Ma	PIP2			3	23	55	16	3	
n = 31	PIP4		6	35	35	23			
	PIP5		3	10	42	42	3		

table 24 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
14 - Ha	MCP2				89	4	7		
n = 39	MCP3			4	86	7	4		
	PIP2				77	10	13		
	PIP3		3		74	13	8	3	

table 25 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +
14 - Ha	MCP2			32	36	32			
n = 39	MCP3			29	54	18			
	PIP2		5	13	31	38	8	5	
	PIP3		3	21	31	31	13	3	

table 26 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-10^0	-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$	$30^0 +$
14 - Ha	MCP2			32	36	32				
n = 39	MCP3			32	43	21		4		
	PIP2		5	8	21	41	18	8		
	PIP3		5	13	28	33	8	8	5	

table 27 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$
15 - ML *n = 22*	PIP5		18	5	50	23	5	

table 28 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$
15 - ML *n = 22*	PIP5		55	36	9	

table 29 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$	$30^0 +$
15 - ML *n = 22*	PIP5		5	5	50	27	9	5	

table 30 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-25^0	-20^0	-15^0	-10^0	-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$
16 - Ka	MCP4						84	10	3	3	
n = 31	MCP5		6	3	3	13	68	3	3		
	PIP4					13	55		32		
	PIP5					3	74	19	3		

table 31 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	$5^0 +$	$10^0 +$	$15^0 +$	$20^0 +$	$25^0 +$	$30^0 +$
16 - Ka	MCP4		3	3	26	52	10	3	3		
n = 31	MCP5				3	29	26	26	10		6
	PIP4			13	35	26	19	6			
	PIP5		6	6	26	26	29	6			

table 32 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +	25^0 +	30^0 +
16 - Ka	MCP4	3	3	23	45	13	6	3	3	
n = 31	MCP5		3	10	26	29	19	13		
	PIP4	10	3	19	39	13	16			
	PIP5	6	3	29	23	16	23			

table 33 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +
17 - Jo *n = 4*	PIP4		25	25	25	25	

table 34 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		-5^0	0^0	5^0 +	10^0 +
17 - Jo *n = 4*	PIP4		50	50	

table 35 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +
17 - Jo *n = 4*	PIP4		25		25	50	

table 36 - appendix 5.3

improvement in joint extension (expressed as a percentage)

		-15^0	-10^0	-5^0	0^0	5^0 +	10^0 +	15^0 +
18 - Wi	MCP2				68	29	4	
n = 28	MCP3		7	14	71	7		
	MCP4		4	4	75	18		
	PIP2			7	75	18		
	PIP3			18	64	14	4	
	PIP4			25	50	25		
	DIP2			11	86	4		
	DIP3			11	82	7		
	DIP4			4	71	25		

table 37 - appendix 5.3

improvement in joint flexion angle (expressed as a percentage)

		- 20^0	- 15^0	- 10^0	- 5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
18 - Wi	MCP2			14	36	29	18	4		
n = 28	MCP3			7	18	68	7			
	MCP4		4	7	25	54	7	4		
	PIP2		4	18	7	46	21	4		
	PIP3			7	25	43	21	4		
	PIP4		4	4	39	36	14	4		
	DIP2			14	21	46	14	4		
	DIP3		4	7	39	32	14		4	
	DIP4			11	25	39	18	7		

table 38 - appendix 5.3

improvement in joint range of motion (expressed as a percentage)

		- 20^0	- 15^0	- 10^0	- 5^0	0^0	5^0 +	10^0 +	15^0 +	20^0 +
18 - Wi	MCP2			11	21	29	32	7		
n = 28	MCP3		4	11	29	43	14			
	MCP4		4	4	29	50	11	4		
	PIP2			18	18	29	32	4		
	PIP3			4	36	36	18	7		
	PIP4			18	29	25	29			
	DIP2			14	29	43	11	4		
	DIP3		4	11	32	43	7		4	
	DIP4			4	21	46	25	4		

table 39 - appendix 5.3

Appendix 5.4

Mean and standard deviation values for the maximum flexion, extension and range of motion angles, recorded before and after each treatment session, for the entire treatment period of each patient

note: refer to section 7.2

		maximum extension angle				maximum flexion angle				maximum range of movement			
		before		*after*		*before*		*after*		*before*		*after*	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
1 - RB	MCP2	-2.31	3.37	-2.18	3.16	56.54	4.26	60.64	4.83	58.85	5.82	62.82	5.75
	MCP3	-6.03	4.83	-6.67	4.85	57.44	5.53	62.31	5.97	63.46	5.21	68.97	6.01
	MCP4	-6.79	5.00	-7.44	5.17	51.54	5.21	55.77	5.13	58.33	6.92	63.21	7.72
	MCP5	-14.10	3.90	-13.72	3.34	45.64	5.90	52.44	8.00	59.74	7.33	66.15	8.95
	PIP2	2.56	3.37	3.72	3.71	71.15	4.73	70.51	6.08	68.59	5.54	66.79	7.88
	PIP3	3.85	2.65	4.87	3.67	79.74	6.69	78.08	7.73	75.90	8.15	73.21	10.09
	PIP4	6.03	3.95	7.05	4.04	84.23	8.95	85.13	7.12	78.21	10.53	78.08	9.10
	PIP5	19.10	5.17	19.23	5.61	77.44	7.92	78.33	6.73	58.33	9.15	59.23	9.17
	DIP2	15.51	5.86	14.10	5.65	42.31	7.155	42.69	7.15	26.79	9.71	28.59	10.56
	DIP3	24.74	5.3	23.85	5.48	31.54	3.43	32.18	3.72	6.79	7.2	8.08	7.56
	DIP4	12.18	3.54	11.92	3.51	25.90	4.22	27.56	4.65	13.72	4.77	15.90	6.29
	DIP5	13.85	5.25	13.72	4.34	33.08	5.84	34.10	5.87	19.23	7.89	20.26	8.00
	MCP2+MCP3+ MCP4+MCP5	-29.23	10.95	-30.00	11.55	211.15	14.74	231.15	17.41	240.38	16.27	261.15	19.69
	PIP2+PIP3+ PIP4+PIP5	31.54	10.93	34.87	13.18	312.56	24.04	312.05	24.30	281.03	28.56	277.31	32.22
	DIP2+DIP3+ DIP4+DIP5	66.28	14.58	63.59	13.77	132.82	15.18	136.54	15.53	66.54	23.86	72.82	25.14
	MCP2+PIP2+ DIP2	15.77	7.21	15.64	7.18	170.00	12.46	173.85	12.11	154.23	15.55	158.21	16.39
	MCP3+PIP3+ DIP3	22.56	7.41	22.05	8.38	168.72	10.84	172.56	11.60	156.41	15.06	156.03	15.41
	MCP4+PIP4+ DIP4	11.41	6.4	11.54	5.79	161.67	13.51	168.46	12.57	150.26	14.54	157.18	14.04
	MCP5+PIP5+ DIP5	18.85	9.09	19.23	7.38	156.15	12.27	164.87	11.79	137.31	14.49	145.64	14.55

		maximum extension angle				maximum flexion angle				maximum range of movement			
		before		*after*		*before*		*after*		*before*		*after*	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
3 - MK	PIP4	8.0	2.45	7.50	2.50	33.50	3.91	35.50	2.69	25.50	5.22	28.0	2.45
4 - GZ	PIP2	48.2	3.86	44.6	5.42	82.3	7.50	83.2	5.75	34.1	9.0	38.6	6.77
	PIP3	40.9	4.17	39.1	5.57	72.7	7.50	70.0	7.39	31.8	10.93	30.9	9.25
	PIP4	48.2	4.41	48.2	3.86	70.5	5.42	67.7	4.94	22.3	8.08	20.0	7.69
	PIP5	45.5	7.22	43.2	5.34	64.6	3.96	63.6	5.26	19.1	9.49	19.6	8.91
5 - CDB	PIP4	21.50	5.50	22.1	5.76	31.25	4.71	35.50	5.45	9.75	6.42	13.40	5.40
6 - AM	PIP3	57.4	4.27	53.4	3.93	90.2	1.72	90.6	2.15	32.8	4.92	37.4	4.72
	PIP4	68.0	3.16	65.6	4.08	90.2	1.72	90.6	1.62	22.2	3.49	25.4	4.22
7 - CM	PIP2	44.0	11.86	40.33	13.96	84.67	4.27	83.33	4.71	40.67	13.52	43.33	13.74
	PIP3	53.67	14.55	44.67	13.30	89.00	5.73	88.67	7.07	35.33	12.91	44.33	11.86
	PIP4	70.33	28.49	66.33	28.12	96.0	13.51	95.0	13.02	25.67	19.69	27.0	20.07
	PIP5	70.67	28.47	63.67	25.48	100.33	16.84	97.00	14.36	29.67	15.87	32.33	14.16
13 - Ma	PIP2	0	0	0	0	44.35	4.71	53.97	5.08	44.35	4.71	53.97	5.08
	PIP4	0	0	0	0	26.61	4.09	30.26	3.82	26.61	4.09	30.26	3.82
	PIP5	0	0	0	0	31.94	3.03	38.61	2.95	31.94	3.03	38.61	2.95
14 - Ha	MCP2	2.7	6.05	1.8	5.21	83.8	5.07	89.1	4.56	81.1	9.67	87.3	8.97
	MCP3	2.5	5.90	1.96	5.23	84.96	5.89	89.54	5.64	82.46	11.09	87.57	10.28
	PIP2	3.7	5.51	1.92	3.69	53.13	6.42	60.49	5.16	49.41	9.20	58.56	7.83
	PIP3	8.9	7.21	7.4	5.53	69.79	5.41	76.56	5.18	60.92	10.88	69.13	8.93
15 - ML	PIP5	31.4	4.88	21.27	5.36	94.6	8.97	97.8	8.36	63.2	10.49	76.8	10.78
16 - Ka	MCP4	-1.0	2.35	-2.3	4.37	70.5	5.53	74.7	5.07	71.4	6.70	76.9	6.31
	MCP5	-16.1	3.29	-13.9	5.19	50.2	7.35	61.9	5.34	66.3	6.09	75.8	6.97
	PIP4	16.1	3.75	15.2	4.30	88.2	6.42	91.8	4.12	72.1	9.23	76.6	7.23
	PIP5	16.9	3.74	15.8	4.04	81.5	6.50	85.6	4.16	64.5	7.97	69.8	6.15

		maximum extension angle				maximum flexion angle				maximum range of movement			
		before		*after*		*before*		*after*		*before*		*after*	
		mean	**std dev**	**mean**	**std dev**	**mean**	**std dev**	**mean**	**std dev**	**mean**	**std dev**	**mean**	**std dev**
17 - Jo	PIP4	26.25	4.15	23.75	8.93	57.5	2.50	60	3.54	31.25	2.17	36.25	7.40
18 - Wi	MCP2	-5.18	3.66	-6.43	4.20	75.18	6.19	73.57	5.95	80.36	6.40	80.18	5.59
	MCP3	-8.57	2.95	-7.50	3.66	72.86	6.04	71.61	6.95	81.43	6.53	79.11	7.20
	MCP4	-8.39	3.00	-8.57	2.95	64.82	7.13	63.04	8.27	73.21	7.93	71.79	8.15
	PIP2	1.43	2.62	0.89	1.91	98.93	5.24	97.68	5.74	97.50	5.75	96.79	5.38
	PIP3	4.29	3.71	4.11	2.34	99.64	4.80	99.11	5.68	95.36	4.99	94.82	6.61
	PIP4	12.68	3.13	12.68	2.83	97.50	5.90	95.71	6.51	84.82	7.13	83.04	8.17
	DIP2	-5.18	2.83	-4.82	3.13	52.68	4.11	51.43	4.79	57.86	4.32	56.07	4.30
	DIP3	-5.54	2.78	-5.36	2.65	60.54	4.50	58.39	5.83	66.07	3.86	63.75	5.11
	DIP4	-8.21	2.40	-9.29	2.20	38.04	5.23	37.50	4.91	46.25	4.15	46.79	3.83

patient #3 - MK

dig 4 PIP right

		1	2	3	4	5	6	7	8	9
	date	16/07/92			17/07/92					
	file name	KRU 10			KRU 11					
	minutes of data	30			45					
	period of cycles	1	2	3	1	2	3	4	5	6
channel 1	maximum	9.2	7.3	-	5.8	5.8	6.6	4.1	4.1	4.1
(actuator 1	minimum	4.2	5.0	-	4.0	4.0	3.9	3.0	3.0	3.0
- force)	mean	6.5	6.2	-	5.0	4.7	5.0	3.7	3.6	3.5
Newtons	S.D.	0.83	0.36	-	0.38	0.30	0.38	0.21	0.22	0.22
	% data above mean	45.04	46.29	-	46.98	52.71	49.70	53.37	54.84	52.85
channel 2	maximum	86.7	87.2	86.7	117.4	117.4	117.2	117.2	117.2	117.3
(actuator 2	minimum	67.5	68.0	67.8	73.1	73.0	72.4	73.2	73.2	73.5
- position)	range	19.2	19.2	18.8	44.3	44.4	44.8	43.9	43.9	43.8
mms	mean	79.64	79.64	79.38	95.19	95.07	95.19	95.57	95.07	95.19
	S.D.	5.57	5.58	5.79	12.16	12.27	12.38	12.55	12.30	12.31
channel 3	maximum	97.3	97.2	96.7	103.0	103.1	103.1	102.7	103.1	103.1
(actuator 1	minimum	79.7	79.3	79.5	86.0	85.9	85.0	85.9	85.9	85.9
- position)	range	17.6	17.8	17.2	16.9	17.2	18.1	16.8	17.2	17.2
mms	mean	85.38	85.38	85.38	95.27	95.14	95.27	95.14	95.27	95.40
	S.D.	4.95	5.00	4.99	6.18	6.23	6.25	6.19	6.21	6.17
channel 4	minimum	-9.9	-8.5	-6.1	-6.6	-6.5	-6.4	-6.6	-6.4	-5.7
(actuator 2	maximum	0.6	0.4	0.6	2.1	1.5	1.6	2.3	1.6	1.5
- force)	mean	-2.3	-2.0	-1.0	-0.4	-0.6	-0.5	-0.5	-0.6	-0.5
Newtons	S.D.	2.53	2.21	1.50	1.54	1.66	1.48	15.75	1.57	1.39
	% data above mean	65.97	65.09	65.77	62.90	65.66	66.79	65.09	65.47	64.40

		10	11	12	13	14	15	16	17
	date	20/07/92							21/07/92
	file name	KRU 13							KRU 14
	minutes of data	49							4
	period of cycles	1	2	3	4	5	6	7	1
channel 1	maximum	13.6	10.7	9.0	7.9	6.9	-	7.1	6.3
(actuator 1	minimum	6.0	5.2	3.7	3.5	3.2	3.2	3.2	5.1
- force)	mean	9.2	7.2	5.0	4.9	4.3	4.3	4.2	5.7
Newtons	S.D.	1.37	1.72	0.92	0.84	0.98	1.00	0.74	0.21
	% data above mean	53.30	-	59.79	63.67	66.40	-	61.71	47.84
channel 2	maximum	107.5	108.2	107.6	107.4	107.6	107.5	107.6	103.0
(actuator 2	minimum	99.0	99.0	99.1	99.2	99.1	99.0	99.0	84.8
- position)	range	8.5	9.3	8.5	8.2	8.5	8.5	8.7	18.2
mms	mean	101.59	101.59	101.72	101.59	101.72	101.72	101.59	90.18
	S.D.	2.06	2.08	2.14	2.08	2.14	2.16	2.15	5.10
channel 3	maximum	104.0	103.9	103.7	103.4	103.9	103.5	103.7	88.3
(actuator 1	minimum	90.6	91.3	91.3	90.5	91.0	91.0	90.4	71.8
- position)	range	13.4	12.6	12.5	12.8	12.8	12.5	13.4	16.6
mms	mean	99.38	99.38	99.38	99.38	99.25	99.25	99.38	83.84
	S.D.	3.39	3.36	3.35	3.32	3.34	3.35	3.34	4.70
channel 4	minimum	-1.2	-	-	-	-	-	-	-5.2
(actuator 2	maximum	-0.1	-	-	-	-	-	-	1.4
- force)	mean	-1.0	-	-	-	-	-	-	-1.4
Newtons	S.D.	0.13	-	-	-	-	-	-	1.45
	% data above mean	-	-	-	-	-	-	-	43.42

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patient #4 - G Z

dig 3 PIP right

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	date	07/02/92						15/07/92						16/07/92					
	file name	ZEI 5						ZEI 27						ZEI 28					
	minutes of data	47						52						53					
	period of cycles	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
channel 1	maximum	2.6	2.6	3.6	4.0	3.5	3.6	8.8	n/a	3.8	3.8	3.8	3.4	4.7	4.8	5.0	5.3	4.9	4.7
(actuator 1	minimum	-4.1	-2.5	-1.5	-1.2	-0.5	-1.0	4.7	2.5	2.1	2.2	1.7	0.9	1.4	1.8	1.8	1.5	1.9	1.9
- force)	mean	-0.2	0.4	0.7	1.0	1.0	0.9	6.6	5.3	2.9	2.9	2.8	3.5	2.8	3.0	3.1	3.2	3.1	3.0
Newtons	S.D.	1.07	0.86	0.88	1.07	0.91	0.84	0.50	2.47	0.26	0.24	0.24	3.28	0.74	0.64	0.64	0.69	0.61	0.61
	% data above mean	60.90	65.63	65.32	66.79	66.60	59.73	47.78	n/a	49.25	47.59	48.35	n/a	64.05	64.45	64.74	59.32	64.68	64.92
channel 2	maximum	107.1	106.6	106.6	106.9	106.9	106.7	86.9	86.8	86.9	86.2	86.9	86.7	89.0	88.8	88.4	88.0	88.5	88.8
(actuator 2	minimum	98.6	98.7	98.6	98.5	98.3	98.2	79.0	79.1	79.4	79.3	79.4	79.6	82.6	82.9	82.6	82.1	82.6	82.5
- position)	range	8.5	7.9	8.0	8.4	8.5	8.5	7.9	7.7	7.5	6.9	7.5	7.0	6.4	5.9	5.8	5.9	5.9	6.3
mms	mean	101.3	101.3	101.3	101.5	101.3	101.3	81.8	81.9	81.9	81.9	81.9	81.9	84.4	84.4	84.4	84.4	84.4	84.4
	S.D.	2.05	2.03	2.07	2.08	2.01	2.05	1.71	1.80	1.74	1.78	1.80	1.67	1.26	1.23	1.23	1.15	1.22	1.24
channel 3	maximum	103.7	103.2	103.7	103.4	103.5	103.2	84.7	84.5	84.6	84.5	85.0	84.5	82.4	82.0	82.0	81.9	82.2	82.6
(actuator 1	minimum	94.9	94.5	94.4	94.8	94.8	94.9	74.6	74.6	75.1	74.6	74.7	74.6	73.8	74.7	74.7	74.6	74.6	74.1
- position)	range	8.9	8.7	9.4	8.6	8.7	8.3	10.1	9.9	9.5	9.9	10.3	9.9	8.6	7.3	7.3	7.3	7.6	8.5
mms	mean	100.5	100.5	100.7	100.7	100.5	100.5	81.0	81.1	81.1	81.1	81.1	81.1	79.9	80.0	80.0	80.0	79.9	80.0
	S.D.	1.87	1.85	1.93	1.88	1.91	1.94	2.37	2.39	2.41	2.40	2.39	2.36	1.72	1.68	1.69	1.65	1.68	1.66
channel 4	minimum	-2.1	-1.6	-0.5	-0.9	-0.9	-2.4	-2.5	-2.2	-3.3	-2.0	-2.9	-4.6	-4.0	-3.7	-4.1	-3.7	-4.1	-3.9
(actuator 2	maximum	5.8	4.8	4.2	3.8	4.0	4.3	2.0	1.5	1.6	1.4	2.1	2.7	5.2	1.8	2.4	3.7	1.1	2.3
- force)	mean	0.8	0.6	0.7	0.4	0.5	0.5	-1.0	-0.9	-1.1	-1.0	-1.2	-1.4	-1.2	-2.4	-2.5	-2.5	-3.0	-2.6
Newtons	S.D.	1.49	1.26	1.12	1.04	1.10	1.14	0.76	0.64	0.83	0.70	0.81	0.98	1.51	1.08	1.18	1.15	1.05	1.08
	% data above mean	34.90	33.65	32.59	33.59	32.72	33.13	30.98	27.20	38.74	28.63	38.09	n/a	32.10	31.21	29.98	28.69	25.86	29.47

		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	date	16/07/92				17/07/92					17/07/92						
	file name	ZEI 29				ZEI 30					ZEI 31						
	minutes of data	50				50					64						
	period of cycles	1	2	3	4	1	2	3	4	5	1	2	3	4	5	6	7
channel 1	maximum	5.6	5.6	6.9	7.0	4.5	4.6	4.7	4.2	4.2	4.6	5.8	5.2	5.0	5.1	4.6	4.7
(actuator 1	minimum	1.4	1.7	1.7	1.9	1.1	0.8	1.0	0.9	0.8	1.0	0.8	1.5	1.4	1.4	1.6	1.3
- force)	mean	3.1	3.5	4.0	3.8	3.4	3.3	3.4	3.2	3.1	3.0	3.3	3.3	3.2	3.2	3.4	3.2
Newtons	S.D.	0.77	0.84	1.10	1.07	0.91	0.86	0.86	0.85	0.81	0.76	0.78	0.64	0.66	0.61	0.66	0.65
	% data above mean	46.43	48.44	50.44	48.43	38.13	37.89	37.70	37.11	37.30	46.86	46.87	46.47	44.43	44.82	44.75	45.62
channel 2	maximum	87.9	87.8	88.3	87.8	87.7	87.8	87.7	87.8	87.9	94.4	94.1	94.2	94.3	94.4	94.1	94.2
(actuator 2	minimum	80.0	79.8	79.5	80.0	81.5	81.4	81.3	81.0	80.9	86.8	86.7	87.0	86.7	86.5	87.0	86.8
- position)	range	7.9	8.0	8.8	7.8	6.1	6.4	6.4	6.8	7.0	7.7	7.4	7.2	7.7	7.9	7.0	7.4
mms	mean	82.9	82.8	82.9	82.9	85.4	85.4	85.4	85.4	85.4	89.8	89.8	89.8	89.8	89.8	89.8	89.8
	S.D.	1.95	1.96	1.95	1.95	1.44	1.41	1.44	1.42	1.40	1.76	1.81	1.77	1.76	1.76	1.79	1.78
channel 3	maximum	89.1	89.0	89.1	88.8	95.0	94.8	94.9	95.1	94.9	96.9	96.9	97.1	96.6	96.8	96.6	97.4
(actuator 1	minimum	78.2	78.1	78.3	78.2	86.4	86.7	86.5	86.4	86.5	85.8	85.4	84.7	85.5	85.8	85.8	85.6
- position)	range	10.9	10.9	10.8	10.7	8.6	8.1	8.3	8.7	8.3	11.2	11.6	12.3	11.0	11.0	10.8	11.8
mms	mean	84.2	84.2	84.2	84.2	89.9	89.7	89.7	89.7	89.9	91.7	91.7	91.7	91.7	91.7	91.7	91.8
	S.D.	2.75	2.77	2.76	2.76	2.15	2.08	2.10	2.11	2.09	2.66	2.69	2.62	2.60	2.63	2.65	2.64
channel 4	minimum	-1.6	-1.6	-2.0	-1.6	-3.0	-3.3	-3.0	-3.4	-3.2	-1.2	-1.4	-1.5	-2.2	-1.8	-1.9	-1.4
(actuator 2	maximum	2.3	1.4	1.2	1.2	2.7	2.8	2.2	2.1	2.8	0.5	0.4	0.6	0.3	0.7	0.6	0.4
- force)	mean	-0.5	-0.7	-0.7	-0.7	0.3	0.2	0.1	0.0	0.1	-0.7	-0.7	-0.7	-0.8	-0.7	-0.8	-0.8
Newtons	S.D.	0.66	0.57	0.56	0.55	1.21	1.20	1.13	1.16	1.14	0.44	0.48	0.39	0.40	0.51	0.48	0.39
	% data above mean	37.52	35.64	34.95	36.08	64.31	64.13	63.37	63.76	64.08	38.63	37.31	41.37	39.63	38.97	37.50	38.31

		35	*36*	*37*	*38*	*39*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*
	date	20/07/92								20/07/92				
	file name	ZEI 23								ZEI 24				
	minutes of data	55								35				
	period of cycles	1	2	3	4	5	6	7	8	1	2	3	4	5
channel 1	maximum	13.6	14.9	-	-	-	-	-	-	-	8.3	7.7	7.2	-
(actuator 1	minimum	2.7	3.3	-	-	-	-	-	-	-	1.7	1.7	1.8	-
- force)	mean	7.9	10.7	-	-	-	-	-	-	-	4.7	4.9	4.7	-
Newtons	S.D.	2.33	3.12	-	-	-	-	-	-	-	1.00	1.02	1.01	-
	% data above mean	53.86	n/a	-	-	-	-	-	-	-	44.36	38.46	42.21	-
channel 2	maximum	88.9	-	-	-	88.3	-	-	-	95.2	94.7	95.1	94.6	94.7
(actuator 2	minimum	81.1	-	-	-	81.0	-	-	-	72.4	72.2	72.2	72.1	72.0
- position)	range	7.8	-	-	-	7.3	-	-	-	22.8	22.5	22.8	22.5	22.7
mms	mean	84.7	-	-	-	84.7	-	-	-	83.3	83.1	83.1	83.3	83.1
	S.D.	1.89	-	-	-	1.89	-	-	-	6.83	6.79	6.81	0.11	6.81
channel 3	maximum	90.9	-	-	-	91.0	-	-	-	98.9	98.1	98.7	98.3	98.5
(actuator 1	minimum	81.9	-	-	-	81.4	-	-	-	72.0	71.1	72.3	72.0	71.9
- position)	range	9.0	-	-	-	9.6	-	-	-	26.8	27.0	26.4	26.3	26.6
mms	mean	86.8	-	-	-	86.8	-	-	-	85.4	85.4	85.4	85.3	85.3
	S.D.	2.04	-	-	-	2.06	-	-	-	7.26	7.29	7.24	7.26	7.18
channel 4	minimum	-0.9	-0.8	-1.0	-1.5	-1.4	-1.3	-1.3	-1.3	-3.0	-3.3	-4.6	-3.0	-2.5
(actuator 2	maximum	9.9	9.6	12.7	11.7	11.7	13.5	13.7	13.7	1.6	1.6	1.3	1.3	3.6
- force)	mean	2.9	2.2	2.9	2.0	2.2	2.8	3.3	3.6	-0.9	-1.0	-1.2	-1.1	-0.6
Newtons	S.D.	2.76	2.57	3.21	2.71	3.05	3.55	3.83	3.80	1.07	0.98	0.99	1.03	1.26
	% data above mean	45.22	43.46	42.64	43.24	43.44	43.31	43.18	45.16	42.85	47.42	44.11	44.53	37.59

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patient #5 - CDB

dig 4 PIP right

		1	2	3	4	5	6		8	9	10	11	12	13	14	15	16
	date	10/09/92					11/09/92				14/09/92			15/09/92			
	file name	BRO 13					BRO 14				BRO 15			BRO 16			
	minutes of data	51					43				42			49			
	period of cycles	1	2	3	4	5	1	2	3	4	1	2	3	1	2	3	4
channel 1	maximum	-	-	-	-	-	-	-	-		-	-		-	-	-	
(actuator 1	minimum	-	-	-	-	-	-	-	-		-	-		-	-	-	
- force)	mean	-	-	-	-	-	-	-	-		-	-		-	-	-	
Newtons	S.D.	-	-	-	-	-	-	-	-		-	-		-	-	-	
	% data above mean	-	-	-	-	-	-	-	-		-	-		-	-	-	
channel 2	maximum	95.7	96.8	96.2	96.2	96.2	116.1	116.1	116.0	116.4	109.2	108.7	109.1	127.6	128.1	127.8	127.4
(actuator 2	minimum	67.7	68.3	68.5	68.1	68.5	87.9	88.4	88.3	88.0	80.8	80.8	80.4	82.0	82.5	82.3	82.1
- position)	range	28.0	28.5	27.7	28.1	27.7	28.2	27.7	27.7	28.4	28.5	28.0	28.7	45.5	45.5	45.5	45.3
mms	mean	81.52	81.77	81.64	81.52	81.64	98.96	98.96	98.96	98.83	93.69	94.32	93.94	97.45	97.45	98.96	98.08
	S.D.	7.77	7.87	7.86	7.87	7.85	8.57	8.54	8.62	8.59	7.96	7.74	7.90	14.40	14.40	14.53	14.50
channel 3	maximum	-	-	-	-	-	-	-	-	-	100.4	100.5	100.7	85.6	85.6	85.8	85.8
(actuator 1	minimum	-	-	-	-	-	-	-	-	-	82.4	83.2	82.3	71.0	70.9	71.5	71.3
- position)	range	-	-	-	-	-	-	-	-	-	18.0	17.3	18.4	14.6	14.8	14.2	14.5
mms	mean	-	-	-	-	-	-	-	-	-	93.98	94.37	94.37	81.02	80.89	81.92	81.40
	S.D.	-	-	-	-	-	-	-	-	-	5.39	5.09	5.22	4.73	4.66	4.02	4.47
channel 4	minimum	-8.8	-5.1	-4.1	-3.4	-3.7	-6.9	-7.5	-2.9	-3.5	-3.8	-4.0	-5.6	-6.0	-6.1	-6.2	-3.8
(actuator 2	maximum	3.1	2.6	3.0	1.9	4.3	1.4	1.5	1.8	1.2	3.1	3.5	4.1	4.1	1.4	2.7	4.2
- force)	mean	-1.4	-0.6	-0.4	-0.1	-0.1	-1.7	-1.4	-0.4	-0.3	0.1	0.3	-0.2	-1.1	-1.5	-1.1	-0.5
Newtons	S.D.	2.20	1.20	1.04	0.85	1.03	2.11	2.32	0.98	0.95	1.07	1.11	1.26	1.90	2.07	2.02	1.28
	% data above mean	64.40	62.81	59.75	59.75	57.14	60.14	62.81	58.61	60.16	62.10	62.81	60.16	55.37	62.81	62.01	57.49

		17	18	19	20	21	22
		16/09/92				24/09/92	
		BRO 17				BRO 23	
		43				53	
		1	2	3	4	1	2
channel 1	maximum	-	-	-	-	-	-
(actuator 1	minimum	-	-	-	-	-	-
- force)	mean	-	-	-	-	-	-
Newtons	S.D.	-	-	-	-	-	-
	% data above mean	-	-	-	-	-	-
channel 2	maximum	103.6	103.6	103.5	103.6	128.6	128.3
(actuator 2	minimum	73.9	74.0	74.1	73.7	93.2	93.8
- position)	range	29.7	29.6	29.4	29.9	35.4	34.5
mms	mean	90.05	90.05	90.05	90.05	105.98	105.86
	S.D.	8.33	8.30	8.32	8.34	10.98	10.99
channel 3	maximum	108.4	108.0	108.2	108.2	96.6	96.7
(actuator 1	minimum	89.4	89.4	89.4	89.0	78.6	77.8
- position)	range	19.0	18.6	18.9	19.3	18.0	18.9
mms	mean	95.40	95.40	95.40	95.40	92.57	92.31
	S.D.	5.31	5.29	5.33	5.39	4.55	4.64
channel 4	minimum	-6.5	-4.8	-4.5	-3.9	-7.0	-5.2
(actuator 2	maximum	3.2	2.9	1.8	2.5	2.0	1.6
- force)	mean	0.0	0.0	0.2	0.3	-2.2	-1.2
Newtons	S.D.	1.79	0.81	1.22	1.40	2.75	1.86
	% data above mean	68.65	62.81	59.75	55.99	55.36	57.87

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patient #6 - AM

digs 4 & 5 PIP right

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	date	20/02/92				26/02/92			10/03/92						
	file name	MAZ 1				MAZ 2			MAZ 11						
	minutes of data	23				20			46						
	period of cycles	1	2	3	4	1	2	3	1	2	3	4	5	6	7
channel 1	maximum	2.6	2.9	3.1	3.0	4.7	4.2	5.8	3.0	5.0	3.3	6.2	6.1	3.0	2.8
(actuator 1	minimum	-1.4	-1.4	-2.8	-3.3	-0.9	0.3	-0.5	-1.8	-1.8	-0.1	-1.9	-1.3	-0.4	0.0
- force)	mean	-0.1	0.2	0.3	0.1	1.6	2.1	2.3	0.2	1.7	1.2	1.9	2.3	1.2	1.2
Newtons	S.D.	1.17	1.13	1.29	1.50	1.19	0.96	1.37	1.17	2.36	0.83	1.79	1.54	0.88	0.75
	% data above mean	58.05	50.40	56.91	53.30	51.91	54.79	55.85	51.27	54.67	55.05	52.33	52.99	50.13	52.09
channel 2	maximum	148.6	149.0	-	-	143.8	143.8	144.0	138.5	138.2	138.7	139.1	139.1	139.1	139.5
(actuator 2	minimum	137.7	137.9	-	-	116.5	116.3	117.0	131.8	131.6	131.6	131.8	131.7	131.6	132.0
- position)	range	10.9	11.2	-	-	27.2	27.5	27.0	6.6	6.6	7.2	7.3	7.4	7.5	7.5
mms	mean	140.87	140.61	-	-	126.19	126.06	126.31	133.71	133.71	133.71	133.84	134.09	133.96	133.96
	S.D.	3.05	2.89	-	-	9.07	9.01	8.96	2.03	1.94	2.11	2.17	2.22	2.39	2.28
channel 3	maximum	131.1	131.2	130.7	130.8	126.8	126.6	127.2	133.0	133.3	133.3	133.3	134.2	133.3	132.9
(actuator 1	minimum	115.9	117.2	116.1	116.8	103.7	103.7	103.5	124.4	124.2	124.7	124.3	124.2	123.8	123.1
- position)	range	15.1	14.0	14.6	14.0	23.1	22.8	23.7	8.6	9.1	8.6	9.0	10.0	9.5	9.8
mms	mean	127.36	127.23	127.36	127.36	120.81	120.81	121.07	130.18	130.44	130.44	130.44	130.57	130.44	130.44
	S.D.	4.17	4.08	4.20	4.03	6.71	6.98	6.60	2.51	2.44	2.44	2.49	2.41	2.53	2.47
channel 4	minimum	-1.1	-1.5	-3.9	-3.1	-1.5	-1.9	-0.9	-0.4	-0.8	-0.2	-0.7	-0.6	-0.6	-0.9
(actuator 2	maximum	4.0	6.0	5.0	7.8	6.7	5.8	6.4	3.6	4.4	3.9	3.0	4.0	2.6	3.2
- force)	mean	0.9	1.2	1.3	2.0	1.3	1.1	1.3	1.3	1.5	1.6	1.1	1.3	0.9	1.0
Newtons	S.D.	1.17	1.67	1.84	2.44	1.86	1.67	1.74	0.91	1.05	0.85	0.95	0.89	0.75	0.80
	% data above mean	45.92	43.07	48.37	46.33	38.82	41.58	40.85	37.38	50.50	51.32	48.57	49.51	48.84	48.99

		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	date	15/03/93								16/03/93						
	file name	MAZ 12								MAZ 13						
	minutes of data	54								52						
	period of cycles	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7
channel 1	maximum	3.6	4.2	3.2	3.2	4.1	2.8	4.1	5.0	3.8	3.0	3.1	4.3	5.9	4.2	4.0
(actuator 1	minimum	-1.1	-2.8	-0.5	-1.8	-1.2	-0.3	-2.3	-2.2	-4.8	0.2	-0.9	0.3	0.4	0.3	0.1
- force)	mean	1.6	1.5	1.3	1.5	1.7	1.3	1.6	1.5	1.5	1.3	1.4	1.7	2.4	2.0	2.0
Newtons	S.D.	1.11	1.22	1.01	1.03	1.15	0.76	1.22	1.55	1.37	0.63	0.88	0.85	1.12	1.02	1.06
	% data above mean	46.55	47.98	52.94	42.09	44.97	44.51	47.87	48.82	41.71	53.83	50.36	57.02	57.95	56.54	51.43
channel 2	maximum	142.5	142.7	143.5	142.4	142.5	142.5	142.4	142.4	141.4	141.6	141.6	141.7	141.4	141.1	141.9
(actuator 2	minimum	124.7	125.1	124.7	124.4	124.8	124.8	124.9	125.1	130.2	130.6	130.1	130.3	130.5	130.3	130.3
- position)	range	17.8	17.7	18.8	17.9	17.7	17.7	17.4	17.3	11.2	11.0	11.5	11.4	10.9	10.8	11.5
mms	mean	131.33	131.96	131.96	132.08	131.71	131.83	131.58	131.96	134.22	134.22	134.09	134.22	134.34	134.09	134.47
	S.D.	5.95	6.27	5.79	5.83	5.76	5.80	5.62	5.74	3.67	3.62	3.88	3.58	3.62	3.62	3.92
channel 3	maximum	136.6	136.9	136.6	136.7	136.6	136.9	136.6	136.5	133.6	133.5	133.4	133.6	133.8	133.6	133.8
(actuator 1	minimum	122.2	121.2	121.2	120.9	120.9	121.6	121.1	121.6	125.2	125.3	124.7	125.0	124.7	124.2	125.4
- position)	range	14.4	15.7	15.4	15.8	15.7	15.3	15.5	14.9	8.5	8.2	8.7	8.6	9.1	9.5	8.3
mms	mean	130.83	131.98	131.98	131.72	132.11	131.72	131.98	131.85	131.21	131.47	131.34	131.08	131.21	131.21	131.34
	S.D.	5.05	4.58	4.66	4.59	4.45	4.55	4.50	4.49	2.24	1.98	2.15	2.53	2.86	2.97	2.58
channel 4	minimum	-0.6	-0.3	-0.7	-0.5	-1.5	-2.1	-1.7	-1.2	-1.5	-0.2	-0.2	-0.2	-0.2	-0.3	-0.4
(actuator 2	maximum	6.9	4.6	5.1	5.4	6.1	3.6	4.6	5.3	5.7	4.5	5.1	3.6	4.4	2.8	2.6
- force)	mean	0.7	1.6	1.2	1.3	1.8	1.7	1.5	1.8	1.7	1.6	1.7	1.5	1.4	1.1	1.2
Newtons	S.D.	2.49	1.24	1.45	1.80	1.45	1.27	1.43	1.39	2.67	1.34	1.35	1.05	1.05	0.88	0.99
	% data above mean	54.26	40.45	40.38	49.00	46.12	51.35	45.12	43.21	59.65	45.69	46.86	50.08	47.78	55.53	55.38

		30	31	32	33	34	35	36	37	38	39	40	41	42
	date	17/03/93						18/03/93						
	file name	MAZ 14						MAZ 15						
	minutes of data	42						53						
	period of cycles	1	2	3	4	5	6	1	2	3	4	5	6	7
channel 1	maximum	4.4	5.7	4.0	4.5	6.7	4.9	2.5	2.8	3.4	2.9	2.4	2.2	4.3
(actuator 1	minimum	-3.2	-3.5	-1.1	-3.7	-1.4	-0.9	-0.6	-2.9	-1.3	-1.6	-1.6	-0.8	0.2
- force)	mean	0.2	1.5	1.4	1.6	2.4	1.8	0.9	1.4	1.7	0.7	0.3	0.7	1.6
Newtons	S.D.	2.22	1.96	1.40	1.69	2.08	1.59	0.77	0.88	0.75	1.19	1.03	0.70	1.37
	% data above mean	53.29	42.29	49.71	48.22	44.89	49.63	46.37	45.60	53.20	45.23	49.74	41.94	35.91
channel 2	maximum	149.0	148.3	148.6	148.5	148.9	149.1	148.5	148.8	148.6	148.0	147.9	147.8	148.0
(actuator 2	minimum	135.7	135.5	135.8	135.5	135.2	136.0	135.5	135.3	135.2	135.6	135.5	134.8	135.1
- position)	range	13.3	12.8	12.8	13.0	13.7	13.2	13.0	13.4	13.4	12.4	12.4	12.9	12.9
mms	mean	140.74	140.49	140.49	140.36	140.49	140.36	141.74	141.87	141.87	141.74	141.62	141.74	141.62
	S.D.	4.48	3.75	•4.25	4.17	4.17	3.94	3.65	3.77	3.80	3.69	3.74	3.82	3.77
channel 3	maximum	147.6	148.5	148.3	148.3	148.2	148.0	144.6	144.3	143.9	144.7	144.4	144.6	144.3
(actuator 1	minimum	132.0	131.6	131.2	131.9	131.3	131.5	138.9	139.6	139.0	139.4	138.4	138.7	139.3
- position)	range	15.7	16.9	17.1	16.4	16.8	16.6	5.6	4.7	4.9	5.3	6.0	5.9	5.0
mms	mean	141.61	142.51	141.99	141.99	141.99	141.87	142.51	142.51	142.38	142.51	142.51	142.64	142.64
	S.D.	5.12	4.82	4.78	4.87	4.97	4.91	1.39	1.17	1.35	1.24	1.43	1.32	1.18
channel 4	minimum	-0.3	-1.1	-0.9	-0.5	-1.2	-1.1	-0.8	-1.2	-1.7	-1.6	-1.6	-0.9	-1.9
(actuator 2	maximum	3.2	3.2	3.3	3.3	3.3	2.5	3.9	3.1	3.0	5.0	6.3	4.2	2.0
- force)	mean	1.1	0.7	0.6	0.8	0.7	0.3	1.0	0.7	0.6	0.9	1.5	1.0	-0.3
Newtons	S.D.	0.71	1.92	0.97	0.86	0.99	0.87	1.16	1.30	1.31	1.66	1.85	1.41	2.67
	% data above mean	53.82	-	40.46	41.05	40.95	45.49	46.13	44.34	44.51	41.36	42.20	38.48	80.93

		43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
	date	23/03/92								25/03/92			31/03/92					
	file name	MAZ 16								MAZ 18			MAZ 25					
	minutes of data	56								38			50					
	period of cycles	1	2	3	4	5	6	7	8	1	1st half	2nd half	1	2	3	4	5	6
channel 1	maximum	5.6	6.1	8.2	5.3	4.2	5.2	2.8	2.7	6.1	6.1	5.2	6.7	4.2	2.1	2.6	3.0	3.5
(actuator 1	minimum	-2.6	-1.8	1.1	1.1	-1.3	-0.1	0.0	0.2	-0.5	-0.5	1.0	-5.0	-4.2	-6.7	-3.8	-5.6	-2.7
- force)	mean	0.9	1.9	3.4	2.9	1.8	1.8	1.1	1.1	2.6	2.4	2.7	-0.9	-0.5	-0.6	-0.5	-0.2	-0.1
Newtons	S.D.	2.01	1.87	1.49	1.04	1.19	2.17	0.76	0.66	1.17	1.24	1.06	1.69	2.24	1.22	1.28	1.37	1.13
	% data above mean	53.78	47.95	54.76	56.50	48.80	67.97	52.41	54.79	51.59	51.16	52.25	53.79	54.20	54.67	54.71	56.56	52.52
channel 2	maximum	166.0	166.1	166.6	166.0	166.3	165.8	166.1	165.8	153.9	-	-	161.1	160.3	160.6	160.6	160.3	161.1
(actuator 2	minimum	154.3	153.9	154.5	154.3	154.4	154.7	154.5	154.2	145.9	-	-	147.6	147.6	147.9	147.8	147.4	147.6
- position)	range	11.7	12.2	12.0	11.7	11.9	11.2	11.5	11.7	8.0	-	-	13.4	12.7	12.7	12.8	12.9	13.4
mms	mean	158.31	158.81	158.56	158.68	158.68	158.81	158.81	158.68	148.27	-	-	152.28	152.16	152.28	152.28	152.28	152.41
	S.D.	3.69	4.01	3.78	3.83	3.78	3.81	3.80	3.82	1.96	-	-	3.75	3.69	3.74	3.73	3.70	3.79
channel 3	maximum	162.7	162.9	163.0	163.2	163.2	163.2	162.3	163.0	150.6	-	-	152.1	151.9	152.4	151.7	152.3	151.9
(actuator 1	minimum	152.3	152.6	152.6	152.8	151.5	151.9	153.4	151.0	140.7	-	-	142.9	143.1	142.4	142.5	143.0	143.1
- position)	range	10.4	10.3	10.4	10.4	11.7	11.3	8.9	12.1	9.9	-	-	9.2	8.7	10.0	9.2	9.2	8.7
mms	mean	158.81	159.45	159.32	159.32	159.32	159.58	159.45	159.45	147.26	-	-	149.18	149.18	149.31	149.18	149.18	149.44
	S.D.	3.28	3.00	3.17	3.04	3.27	3.16	2.97	3.11	2.38	-	-	1.99	1.96	2.03	2.00	2.15	1.96
channel 4	minimum	-4.0	-0.3	-0.2	-0.7	-1.7	0.1	0.1	-0.3	-0.7	-0.5	-0.6	-3.1	-3.6	-2.4	-5.5	-2.9	-3.3
(actuator 2	maximum	5.8	3.8	3.9	3.3	4.8	4.3	4.2	4.4	4.5	4.5	3.7	5.4	5.0	5.3	5.4	5.5	5.4
- force)	mean	0.5	1.3	1.1	1.1	1.2	1.5	1.5	1.4	1.1	1.2	1.1	0.7	0.6	0.7	0.6	0.5	0.8
Newtons	S.D.	2.44	1.16	0.98	0.98	1.16	1.16	1.09	1.08	1.09	1.30	0.84	1.97	2.09	1.95	2.25	2.08	2.03
	% data above mean	52.43	46.96	39.84	50.71	44.93	41.28	44.49	44.53	47.87	46.63	45.69	44.93	50.14	43.15	45.10	46.56	46.18

		60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76
	date	04/02/92			04/05/92			04/06/92						04/06/92				
	file name	MAZ 26			MAZ 27			MAZ 28						MAZ 29				
	minutes of data	31			39			41						32				
	period of cycles	1	2	3	1	2	3	1	2	3	4	5	6	1	2	3	4	5
channel 1	maximum	3.3	3.2	5.2	3.3	3.6	5.8	2.3	3.0	4.3	4.2	2.8	2.8	2.9	3.0	3.3	5.3	5.1
(actuator 1	minimum	-1.7	-3.3	-1.7	-1.5	-3.5	-2.9	-7.0	-6.3	-3.3	-2.9	-1.5	-1.5	-1.3	-1.1	-1.4	-0.6	-0.2
- force)	mean	0.7	0.6	1.2	0.4	0.7	1.2	-2.2	-1.7	0.4	0.9	0.7	0.5	0.1	0.6	0.8	1.6	1.2
Newtons	S.D.	1.16	1.54	1.49	1.18	1.26	1.82	1.87	1.88	1.82	1.40	0.88	0.89	1.12	0.97	1.14	1.24	1.25
	% data above mean	58.93	66.10	61.08	60.35	51.48	54.80	-	51.14	45.01	44.90	48.91	50.04	54.61	54.78	60.10	54.55	63.92
channel 2	maximum	152.8	152.4	152.8	159.4	159.3	159.4	161.6	161.3	161.4	161.3	161.1	161.4	154.7	155.9	154.7	154.5	154.3
(actuator 2	minimum	139.4	139.1	139.0	150.9	150.7	151.0	145.8	145.6	145.6	145.8	145.8	145.4	146.3	146.8	146.6	146.0	146.8
- position)	range	13.4	13.3	13.8	8.5	8.7	8.4	15.8	15.7	15.8	15.6	15.3	16.1	8.4	9.2	8.0	8.5	7.5
mms	mean	143.25	143.37	143.37	153.16	153.29	153.29	151.15	151.15	151.41	151.28	151.28	151.28	148.64	148.90	148.90	148.90	148.90
	S.D.	3.79	3.78	3.84	2.00	2.10	2.04	4.64	4.64	4.66	4.59	4.64	4.66	2.17	2.24	2.54	2.21	2.50
channel 3	maximum	142.6	142.5	142.9	147.8	147.6	147.9	150.6	151.0	151.0	151.1	151.2	151.5	145.5	145.3	146.0	145.6	145.1
(actuator 1	minimum	129.7	128.5	128.8	137.8	138.4	138.3	140.5	141.1	140.7	140.8	141.2	141.1	136.5	135.2	134.9	136.9	135.1
- position)	range	13.0	14.0	14.1	10.0	9.2	9.6	10.1	9.9	10.3	10.3	10.0	10.4	9.0	10.1	11.0	8.7	10.0
mms	mean	138.91	138.91	139.04	145.07	145.07	145.20	147.90	148.03	148.16	148.16	148.28	148.16	142.38	142.38	142.38	142.64	142.64
	S.D.	3.42	3.34	3.40	2.18	2.17	2.13	2.19	2.22	2.31	2.31	2.32	2.26	2.73	2.73	3.42	2.42	3.10
channel 4	minimum	-3.3	-0.5	-1.3	-1.5	-1.8	-1.3	-3.8	-3.9	-3.6	-1.5	-1.2	-1.2	-0.7	1.1	0.9	0.5	0.5
(actuator 2	maximum	6.8	5.9	5.2	5.4	5.2	5.3	6.4	5.4	5.2	3.5	3.3	3.6	5.8	5.0	3.8	4.3	3.9
- force)	mean	0.7	1.3	1.0	1.2	1.1	1.3	0.8	0.4	0.7	0.9	0.9	0.9	2.0	2.7	2.1	1.8	2.1
Newtons	S.D.	1.67	1.34	1.38	1.67	1.61	1.53	2.09	2.01	1.68	1.07	0.95	1.01	1.36	0.95	0.84	1.16	0.91
	% data above mean	40.30	34.95	35.79	45.77	47.46	46.64	43.86	44.97	44.41	46.16	42.63	43.02	45.09	46.87	46.27	42.89	50.95

		77	78	79	80	81	82	83	84	85	86	87	88
	date	04/12/92						13/04/92					
	file name	MAZ 31						MAZ 32					
	minutes of data	40						39					
	period of cycles	1	2	3	4	5	6	1	2	3	4	5	6
channel 1	maximum	2.4	3.9	4.3	4.9	8.0	4.1	3.6	4.1	3.7	5.5	5.5	5.7
(actuator 1	minimum	-3.3	-2.4	-1.7	-1.9	-7.8	-1.5	-2.6	-1.7	-1.0	-1.3	-1.4	-1.8
- force)	mean	-1.1	n/a	0.4	0.5	0.6	0.4	-0.3	0.5	0.8	3.7	1.9	2.2
Newtons	S.D.	2.54	n/a	1.60	1.90	4.05	1.46	3.00	2.74	2.94	4.64	1.65	1.64
	% data above mean	48.29	n/a	58.80	56.27	-	59.13	57.91	56.54	60.82	n/a	58.35	57.11
channel 2	maximum	162.8	162.7	162.9	162.4	162.8	162.6	163.1	163.6	163.3	163.5	163.6	162.9
(actuator 2	minimum	154.8	154.2	154.5	154.8	154.2	154.8	153.4	153.5	153.3	153.3	153.2	153.3
- position)	range	8.0	8.5	8.4	7.7	8.7	7.8	9.7	10.0	10.0	10.2	10.4	9.7
mms	mean	156.93	157.18	157.18	157.05	157.05	157.18	156.30	156.05	156.17	156.17	156.17	155.92
	S.D.	2.22	2.52	2.57	2.19	2.45	2.46	2.65	2.50	2.62	2.62	2.58	2.40
channel 3	maximum	155.3	156.1	155.5	156.0	156.1	155.6	151.2	151.0	151.2	151.1	151.0	150.9
(actuator 1	minimum	145.2	146.6	145.5	145.5	145.8	145.6	139.6	138.5	138.7	139.3	138.8	138.9
- position)	range	10.1	9.5	10.0	10.5	10.3	10.0	11.7	12.5	12.6	11.8	12.2	11.9
mms	mean	152.39	152.65	152.78	152.78	152.78	152.65	147.64	147.51	147.77	147.77	147.77	147.64
	S.D.	2.80	2.73	2.74	2.79	2.78	2.97	2.84	2.96	2.93	2.87	2.86	2.96
channel 4	minimum	-4.0	-1.4	-1.0	-0.1	-0.2	0.1	-5.0	-2.0	-3.4	-1.9	-0.5	-0.3
(actuator 2	maximum	4.6	4.2	3.9	5.0	4.8	4.5	5.9	6.9	6.5	5.9	5.3	5.1
- force)	mean	0.4	0.7	0.8	1.5	1.3	1.5	1.0	1.2	1.1	1.2	1.6	1.4
Newtons	S.D.	1.50	1.29	1.12	1.23	1.20	1.07	1.65	1.56	1.54	1.25	1.33	1.17
	% data above mean	46.70	44.84	41.30	41.26	46.12	44.27	43.85	38.15	39.79	36.91	42.02	44.03

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patient #7 - CM

digs 4 & 5 PIP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	date	09/09/92				09/09/92			10/09/92			10/09/92				11/09/92			
	file name	MAR 5				MAR 7			MAR 9			MAR 10				MAR 11			
	minutes of data	31				25			33			34				35			
	period of cycles	1	2	3	4	1	2	3	1	2	3	1	2	3	4	1	2	3	4
channel 1	maximum	-	-	-	-	-	-	-	7.3	9.8	8.1	8.3	8.3	9.1	7.3	-	-	-	-
(actuator 1	minimum	-	-	-	-	-	-	-	2.9	5.1	4.8	3.9	4.0	4.2	4.0	-	-	-	-
- force)	mean	-	-	-	-	-	-	-	5.6	6.6	6.7	6.5	6.5	6.6	6.2	-	-	-	-
Newtons	S.D.	-	-	-	-	-	-	-	0.90	0.60	0.70	0.94	0.84	0.92	0.74	-	-	-	-
	% data above mean	-	-	-	-	-	-	-	38.29	52.70	51.43	43.21	41.78	47.55	42.80	-	-	-	-
channel 2	maximum	126.9	126.2	126.1	126.1	131.8	131.5	131.7	125.8	126.1	126.1	124.2	123.6	124.4	124.2	117.9	118.8	119.2	118.7
(actuator 2	minimum	105.2	105.5	105.6	105.4	123.8	123.7	123.9	94.6	94.7	94.3	101.1	101.1	101.0	100.7	96.1	96.4	96.8	96.3
- position)	range	21.7	20.7	20.5	20.7	8.0	7.8	7.8	31.2	31.4	31.7	23.1	22.5	23.5	23.5	21.8	22.3	22.3	22.3
mms	mean	116.15	116.15	116.02	116.02	125.93	125.93	125.93	110.13	110.13	110.38	113.01	113.01	113.14	113.14	107.62	107.87	107.74	107.62
	S.D.	5.69	5.67	5.63	5.61	1.54	1.59	1.50	9.56	9.60	9.71	6.19	6.17	6.25	6.23	5.70	5.78	5.74	5.64
channel 3	maximum	125.6	125.8	125.6	125.7	132.9	132.8	133.0	131.1	130.7	131.1	126.3	126.5	127.2	126.8	116.8	117.1	117.2	117.0
(actuator 1	minimum	110.9	110.5	110.7	110.0	114.0	114.1	114.4	94.2	94.4	94.5	109.3	109.4	109.1	109.5	101.4	101.9	102.1	101.7
- position)	range	14.6	15.3	14.9	15.7	18.9	18.6	18.6	36.8	36.3	36.6	17.1	17.1	18.1	17.3	15.4	15.1	15.1	15.3
mms	mean	118.76	118.63	118.63	118.76	124.66	124.79	124.79	112.98	112.60	113.24	116.58	116.83	116.70	116.70	110.03	110.03	110.16	110.03
	S.D.	4.80	4.76	4.79	4.81	5.31	5.33	5.31	10.09	9.97	10.25	5.25	5.35	5.31	5.31	4.79	4.82	4.80	4.75
channel 4	minimum	-0.2	-0.2	-0.2	0.0	0.3	0.2	0.1	-0.9	-0.7	-0.6	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.2	-0.2
(actuator 2	maximum	3.8	3.7	3.6	3.0	5.0	4.3	4.1	4.9	4.5	4.0	4.6	3.8	3.6	3.2	5.6	4.8	4.7	5.3
- force)	mean	1.3	1.1	1.1	1.1	1.6	1.3	1.2	1.2	1.0	0.9	1.9	1.5	1.4	1.3	2.0	1.5	1.5	1.7
Newtons	S.D.	0.94	0.80	0.78	0.68	0.98	0.86	0.80	1.39	1.27	1.11	1.03	0.93	0.85	0.81	1.30	1.18	1.16	1.22
	% data above mean	40.71	42.84	42.08	42.55	26.48	23.00	25.77	38.62	39.86	40.22	46.41	46.27	45.48	45.71	41.40	40.49	38.98	40.83

		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
	date	11/09/92			14/09/92			14/09/92				16/09/92			17/09/92	
	file name	MAR 12			MAR 13			MAR 14				MAR 18			MAR 19	
	minutes of data	29			32			27				23			34	
	period of cycles	1	2	3	1	2	3	1	2	3	4	1	2	3	1	2
channel 1	maximum	9.4	9.0	8.9	-	-	-	8.2	7.8	8.1	10.1	-	-	-	6.1	6.0
(actuator 1	minimum	6.0	6.6	5.9	-	-	-	1.0	2.2	2.8	2.1	-	-	-	-0.1	0.4
- force)	mean	7.7	7.9	7.5	-	-	-	5.8	6.0	6.3	6.3	-	-	-	4.6	4.6
Newtons	S.D.	0.69	0.61	0.69	-	-	-	2.05	1.63	1.47	1.45	-	-	-	1.20	1.10
	% data above mean	47.18	51.39	53.03	-	-	-	40.90	39.78	40.42	40.08	-	-	-	31.05	28.52
channel 2	maximum	129.4	129.3	129.6	109.7	110.0	110.3	123.7	123.7	123.8	123.9	140.4	140.5	140.7	102.5	102.7
(actuator 2	minimum	110.9	111.0	110.5	100.2	100.0	100.2	97.5	98.3	98.6	98.2	105.9	105.1	105.1	84.0	84.2
- position)	range	18.6	18.3	19.1	9.5	10.0	10.0	26.2	25.3	25.2	25.7	34.5	35.4	35.6	18.4	18.6
mms	mean	119.16	119.16	119.41	104.10	104.10	104.10	111.63	111.63	111.63	111.76	125.81	125.31	125.31	96.32	96.32
	S.D.	6.14	6.17	6.28	3.00	2.95	2.96	6.83	6.86	6.80	6.96	10.51	10.50	10.50	5.45	5.45
channel 3	maximum	129.0	137.0	137.2	114.8	114.7	114.7	125.2	125.4	125.6	125.4	147.4	147.3	147.3	115.4	116.2
(actuator 1	minimum	104.8	104.4	104.5	95.7	94.9	96.2	109.1	109.1	109.1	108.9	124.8	124.8	124.8	99.8	99.4
- position)	range	24.3	32.6	32.7	19.1	19.8	18.5	16.0	16.3	16.4	16.6	22.6	22.5	22.5	15.7	16.8
mms	mean	121.20	121.33	121.45	105.67	105.54	105.54	115.81	115.81	115.68	115.81	132.75	132.24	132.37	104.64	104.89
	S.D.	8.65	8.60	8.73	4.97	4.89	4.91	5.00	5.04	4.99	5.02	7.05	6.93	6.99	4.49	4.65
channel 4	minimum	0.0	-0.1	-0.3	0.0	0.2	0.2	0.3	0.2	0.2	0.0	-0.3	-0.4	-0.4	-0.6	-0.6
(actuator 2	maximum	5.3	4.5	3.5	2.0	2.0	2.0	2.5	2.0	1.8	1.6	2.4	1.8	1.9	4.3	2.4
- force)	mean	1.6	1.4	1.1	0.8	0.9	0.8	1.2	1.0	1.0	0.9	1.0	0.8	0.7	1.1	1.0
Newtons	S.D.	1.42	1.28	1.03	0.43	0.39	0.38	0.46	0.38	0.37	0.34	0.56	0.49	0.46	0.73	0.67
	% data above mean	37.59	37.38	38.61	39.59	38.11	38.33	52.03	54.02	53.34	54.17	51.68	49.94	50.83	57.44	56.30

	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
date	17/09/92				18/09/92		18/09/92				24/09/92				
file name	MAR 20				MAR 21		MAR 22				MAR 23				
minutes of data	31				27		32				40				
period of cycles	1	2	3	4	1	2	1	2	3	4	1	2	3	4	5
channel 1 maximum	-	-	-	-	5.8	6.8	-	-	-	-	-	-	-	-	-
(actuator 1 minimum	-	-	-	-	1.0	2.2	-	-	-	-	-	-	-	-	-
- force) mean	-	-	-	-	4.4	5.0	-	-	-	-	-	-	-	-	-
Newtons S.D.	-	-	-	-	0.88	0.96	-	-	-	-	-	-	-	-	-
% data above mean	-	-	-	-	41.54	51.12	-	-	-	-	-	-	-	-	-
channel 2 maximum	113.6	113.5	113.0	113.3	123.0	123.0	134.0	134.2	134.2	134.0	96.1	96.1	96.7	96.2	96.2
(actuator 2 minimum	84.9	84.7	84.7	84.3	104.2	104.0	106.5	106.9	107.0	107.1	78.6	79.1	79.0	79.3	78.5
- position) range	28.7	28.9	28.4	29.0	18.8	19.1	27.5	27.4	27.2	26.9	17.4	16.9	17.7	16.9	17.7
mms mean	102.85	102.85	102.72	102.85	114.27	114.52	120.92	121.29	121.17	121.17	89.05	89.17	89.17	89.30	89.17
S.D.	8.47	8.58	8.51	0.66	5.44	5.47	8.62	8.70	8.62	8.61	4.70	4.73	4.74	4.72	4.73
channel 3 maximum	127.5	127.0	127.5	127.1	128.8	129.2	142.3	141.2	141.5	141.5	101.9	101.8	102.6	101.8	102.6
(actuator 1 minimum	102.1	102.2	102.5	102.3	105.9	106.8	106.7	106.4	106.7	106.7	86.8	86.4	86.5	86.8	86.5
- position) range	25.4	24.8	25.0	24.8	22.8	22.3	35.6	34.8	34.8	34.8	15.1	15.4	16.0	15.0	16.0
mms mean	110.29	110.29	110.41	110.41	117.48	117.60	124.15	124.66	124.54	124.54	92.57	92.83	92.70	92.83	92.83
S.D.	7.30	7.30	7.31	7.34	5.84	5.92	9.48	9.68	9.56	9.56	4.33	4.47	4.44	4.45	4.44
channel 4 minimum	0.0	0.1	0.2	0.2	-0.1	-0.1	-0.2	-0.2	-0.3	-0.5	-0.1	-0.2	-0.8	-0.2	-0.2
(actuator 2 maximum	2.1	2.0	2.0	1.9	3.4	1.9	3.9	3.8	3.4	3.2	4.2	3.9	3.7	3.7	3.5
- force) mean	1.2	1.1	1.1	1.1	0.9	0.7	1.5	1.5	1.3	1.2	2.4	2.2	2.0	1.9	1.9
Newtons S.D.	0.48	0.44	0.42	0.41	0.64	0.49	1.16	1.06	0.95	0.86	1.07	1.01	0.96	0.93	0.93
% data above mean	54.72	55.90	54.85	56.69	45.18	43.67	40.94	41.88	41.38	43.03	54.45	53.27	54.04	52.03	52.70

	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
date	24/09/92						30/09/92						01/10/92			
file name	MAR 24						MAR 29						MAR31D			
minutes of data	39						47						37			
period of cycles	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4
channel 1 maximum	-	-	-	-	-	-	-	-	-	-	-	-	4.7	4.6	5.8	6.4
(actuator 1 minimum	-	-	-	-	-	-	-	-	-	-	-	-	1.6	2.1	2.5	3.0
- force) mean	-	-	-	-	-	-	-	-	-	-	-	-	3.0	3.2	4.2	4.6
Newtons S.D.	-	-	-	-	-	-	-	-	-	-	-	-	0.79	0.56	0.74	0.72
% data above mean	-	-	-	-	-	-	-	-	-	-	-	-	51.01	53.54	51.05	53.33
channel 2 maximum	116.5	116.3	116.8	116.0	116.3	116.4	134.2	134.7	134.5	134.8	134.7	134.6	126.2	126.3	125.9	126.7
(actuator 2 minimum	105.1	105.2	105.5	105.1	105.1	105.2	123.6	123.4	123.4	123.4	123.4	123.0	111.1	111.1	111.1	111.4
- position) range	11.4	11.0	11.3	10.9	11.2	11.2	10.7	11.3	11.0	11.4	11.3	11.5	15.1	15.2	14.8	15.3
mms mean	110.25	110.25	110.25	110.25	110.38	110.38	127.94	128.07	128.07	127.94	128.07	128.07	117.40	117.40	117.40	117.53
S.D.	3.39	3.37	3.37	-	3.40	3.41	3.28	3.32	3.40	3.38	3.40	3.36	4.45	4.48	4.45	4.51
channel 3 maximum	122.1	122.6	121.3	121.6	121.8	121.8	138.4	138.3	138.7	139.2	138.3	138.9	127.6	127.4	127.5	127.9
(actuator 1 minimum	102.3	103.4	103.1	103.1	103.5	103.7	121.8	121.2	122.0	121.6	121.8	122.1	108.9	108.7	109.0	108.7
- position) range	19.8	19.3	18.2	18.5	18.4	18.1	16.6	17.1	16.7	17.6	16.4	16.8	18.7	18.6	18.5	19.1
mms mean	112.85	112.85	112.85	112.85	112.85	112.85	130.57	130.57	130.70	130.57	130.70	130.70	119.66	119.66	119.66	119.79
S.D.	4.61	4.70	4.66	4.69	4.67	4.68	4.25	4.25	4.30	4.33	4.33	4.35	5.11	5.12	5.12	5.14
channel 4 minimum	0.4	0.6	0.4	0.4	0.6	0.6	0.4	0.0	-0.1	0.0	-0.2	0.0	-3.1	-3.0	-3.3	-3.5
(actuator 2 maximum	7.6	6.3	6.1	5.9	6.0	5.8	4.0	3.5	3.2	2.9	3.0	5.7	1.3	0.7	0.7	0.7
- force) mean	3.3	2.7	2.7	2.6	2.6	2.5	1.5	1.1	1.0	0.9	0.8	1.1	-0.9	-1.7	-1.6	-1.9
Newtons S.D.	2.07	1.70	1.65	1.62	1.60	1.61	0.86	0.73	0.75	0.66	0.66	0.92	0.89	0.83	0.94	0.89
% data above mean	43.37	43.65	43.74	43.74	42.97	43.53	38.97	40.08	38.55	39.62	38.02	38.60	45.99	46.92	46.72	46.70

		65	66	67	68	69
	date	01/10/92				
	file name	MARDIG				
	minutes of data	38				
	period of cycles	1	2	3	4	5
channel 1	maximum	5.7	6.6	5.8	5.8	5.7
(actuator 1	minimum	-3.8	-4.0	-1.0	-1.7	-2.5
- force)	mean	1.9	2.4	3.0	3.1	3.1
Newtons	S.D.	2.41	2.20	1.53	1.38	1.49
	% data above mean	46.21	46.36	48.00	48.33	47.73
channel 2	maximum	145.8	145.3	145.0	145.8	145.5
(actuator 2	minimum	112.0	112.5	112.3	112.4	112.3
- position)	range	33.8	32.7	32.7	33.4	33.2
mms	mean	125.18	125.06	125.18	125.31	125.06
	S.D.	10.38	10.39	10.45	10.52	10.43
channel 3	maximum	134.8	134.9	134.8	134.8	134.9
(actuator 1	minimum	102.8	102.7	102.7	102.7	102.6
- position)	range	32.0	32.2	32.1	32.1	32.3
mms	mean	124.15	124.15	124.15	124.28	124.15
	S.D.	9.50	9.60	9.62	9.55	9.58
channel 4	minimum	-0.4	-0.2	0.3	0.0	0.1
(actuator 2	maximum	5.6	5.1	4.0	3.7	3.7
- force)	mean	1.5	1.2	1.1	1.0	1.0
Newtons	S.D.	1.18	-	0.90	0.80	0.82
	% data above mean	30.51	29.16	28.59	28.51	28.73

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patient #8 - IS

digs 2 & 3 MCP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	date	2/1/93					5/1/93				7/1/93				8/1/93				20/1/93				
	file name	SIN 20					SIN 21				SIN 24				SIN 26				SIN 29				
	minutes of data	46					45				45				45				45				
	period of cycles	1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	5
channel 1	maximum	3.6	2.5	3.3	2.2	2.8	0.7	0.9	0.7	1.8	1.7	1.3	1.4	1.3	0.4	0.4	0.3	0.1	2.8	2.5	2.7	2.4	2.1
(actuator 1	minimum	-3.3	-2.3	-1.8	-1.9	-5.0	-3.9	-3.0	-3.2	-4.5	-5.1	-2.8	-3.5	-2.9	-2.9	-2.9	-2.9	-3.3	-1.2	-1.1	-1.4	-1.4	-0.9
- force)	mean	0.0	0.0	-0.1	-0.1	-0.3	-0.8	-0.6	-0.6	-0.6	-0.9	-0.6	-1.0	-0.8	-0.9	-0.6	-0.7	-1.0	0.2	0.2	0.2	0.2	0.3
Newtons	S.D.	0.80	0.78	0.64	0.57	0.62	0.75	0.56	0.58	0.73	0.84	0.64	0.77	0.62	0.50	0.53	0.50	0.54	0.69	0.68	0.74	0.70	0.58
	% data above mean	59.36	63.53	65.89	59.70	54.57	44.45	39.54	42.86	-	44.06	47.72	51.89	51.12	50.34	44.71	40.65	42.63	68.00	66.78	57.61	58.62	67.08
channel 2	maximum	145.8	146.0	145.6	146.3	145.3	159.6	159.8	159.4	158.9	153.5	154.3	153.9	154.0	144.3	144.8	144.5	144.1	150.5	149.9	149.9	150.5	150.2
(actuator 2	minimum	96.6	95.6	96.2	96.4	96.2	100.2	99.5	100.1	100.0	91.4	92.4	92.3	92.2	87.9	88.9	88.9	88.8	92.8	94.1	93.4	92.8	93.8
- position)	range	49.2	50.4	49.4	49.8	49.1	59.3	60.4	59.3	59.0	62.1	61.9	61.6	61.9	56.3	55.8	55.6	55.3	57.7	55.8	56.5	57.7	56.3
mms	mean	122.55	122.67	122.67	122.30	123.30	131.46	130.83	130.58	130.58	124.93	124.55	124.55	124.55	117.53	117.28	117.40	117.15	123.17	122.92	122.80	123.68	123.30
	S.D.	14.12	13.98	13.93	14.28	13.75	16.54	16.79	16.93	16.94	17.15	17.29	17.37	17.30	15.60	15.55	15.47	15.62	15.63	15.87	15.86	15.38	15.65
channel 3	maximum	152.8	153.0	152.4	152.8	152.4	165.5	165.1	165.2	164.6	158.8	160.2	158.8	158.8	149.2	148.8	149.6	148.8	154.4	154.4	154.2	155.3	154.7
(actuator 1	minimum	106.6	106.1	106.6	105.8	105.8	109.6	109.4	109.6	109.9	103.9	103.5	103.9	103.6	97.6	98.3	98.1	98.2	106.1	105.5	105.9	105.8	105.5
- position)	range	46.2	47.0	45.8	47.0	46.6	55.8	55.7	55.6	54.7	54.9	56.7	54.9	55.2	51.6	50.4	51.5	50.6	48.4	48.9	48.3	49.6	49.2
mms	mean	126.33	126.46	126.46	126.33	127.23	135.32	134.55	134.68	134.68	128.77	128.77	128.51	128.51	121.45	120.94	120.94	120.68	127.36	127.10	127.62	127.62	127.49
	S.D.	13.77	13.79	13.71	13.81	13.68	16.33	16.61	16.55	16.57	16.64	16.64	16.75	16.74	15.02	15.22	15.17	15.29	14.76	14.90	14.67	14.71	14.79
channel 4	minimum	-4.9	-2.4	-2.4	-5.8	-6.8	-2.9	-2.6	-5.2	-2.8	-4.1	-2.4	-2.5	-2.5	-1.1	-1.3	-1.4	-1.5	-1.4	-1.4	-1.6	-2.7	-1.0
(actuator 2	maximum	5.3	4.1	5.6	6.5	5.0	6.7	6.2	4.4	0.7	10.4	10.2	8.3	8.8	5.3	4.2	3.5	2.9	5.1	3.9	3.8	3.8	3.9
- force)	mean	-0.2	-0.1	-0.4	-0.8	-1.4	0.0	-0.1	-0.4	-0.2	0.1	0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.2	0.0	0.0	-0.3	-0.2	0.1
Newtons	S.D.	1.20	0.66	0.45	1.05	1.13	1.30	0.94	1.14	0.43	2.09	1.37	1.24	1.16	0.65	0.56	0.51	0.50	0.77	0.62	0.66	0.77	0.66
	% data above mean	39.45	40.64	49.64	58.56	51.97	47.52	52.00	65.49	66.10	22.65	31.97	44.80	45.37	33.18	49.59	55.10	53.72	30.39	44.14	47.10	56.90	43.35

		23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
	date	22/1/93				23/1/93			26/1/93				2/2/93		2/4/93		2/4/93	2/6/93				2/6/93	
	file name	SIN 32				SIN 34			SIN 36				SIN 44		SIN 51		SIN 52	SIN 56				SIN 57	
	minutes of data	45				35			44				45		45		15	45				36	
	period of cycles	1	2	3	4	1	2	3	1	2	3	4	2	3	1	2	1	1	2	3	4	1	2
channel 1	maximum	0.4	1.0	0.0	0.0	1.3	1.2	1.3	0.6	0.4	0.3	0.5	0.2	0.4	1.6	0.9	3.2	1.3	1.5	1.2	1.0	2.3	2.2
(actuator 1	minimum	-2.7	-3.1	-3.4	-3.9	-3.4	-3.0	-3.7	-3.1	-2.8	-2.8	-3.2	-1.5	-2.2	-2.2	-1.8	-0.5	-2.3	-1.3	-1.6	-1.7	-0.7	-0.6
- force)	mean	-1.0	-0.9	-0.8	-0.9	-1.0	-0.7	-0.8	-0.9	-0.6	-0.7	-0.8	-0.5	-0.5	-0.4	-0.3	0.0	-0.6	-0.4	-0.5	-0.5	-0.1	-0.1
Newtons	S.D.	0.60	0.70	0.68	0.62	0.95	0.81	0.91	0.60	0.45	0.48	0.63	0.28	0.27	0.33	0.29	0.63	0.36	0.29	0.27	0.33	0.52	0.41
	% data above mean	38.98	39.64	29.89	-	-	39.20	39.57	40.27	44.98	44.02	46.43	44.68	42.96	43.46	43.12	74.24	44.07	58.09	56.36	-	-	71.64
channel 2	maximum	152.0	152.7	151.9	152.4	163.7	164.7	163.5	148.5	148.5	149.0	149.6	133.5	133.7	123.9	124.7	117.7	140.2	141.1	140.4	140.6	126.2	127.1
(actuator 2	minimum	94.3	94.4	94.2	93.7	97.8	97.7	97.7	91.1	90.0	91.3	90.0	84.4	85.2	91.8	91.3	84.5	94.7	95.2	94.7	94.1	88.5	87.3
- position)	range	57.7	58.2	57.7	58.7	65.9	67.0	65.7	57.5	58.5	57.7	59.6	49.1	48.6	32.1	33.4	33.1	45.5	45.9	45.7	46.5	37.6	39.8
mms	mean	123.43	123.30	122.92	122.92	131.96	130.33	130.70	122.17	121.42	121.54	121.29	109.00	108.75	107.36	107.11	99.96	117.40	116.90	117.03	117.28	107.24	106.61
	S.D.	15.52	15.57	15.78	15.80	17.93	18.41	18.17	15.77	16.12	16.07	16.31	13.16	13.20	9.20	9.23	9.29	12.89	13.15	13.07	13.02	10.29	10.49
channel 3	maximum	152.4	152.3	151.9	152.1	161.9	162.9	162.0	155.3	154.7	154.6	154.7	134.4	134.2	127.6	127.7	117.0	143.4	144.3	143.1	143.0	125.9	126.8
(actuator 1	minimum	102.2	101.8	102.2	102.2	106.7	106.4	106.6	102.6	102.6	103.0	102.5	89.2	89.6	93.3	92.7	84.1	96.9	97.1	96.7	96.2	90.4	89.5
- position)	range	50.2	50.4	49.7	49.9	55.2	56.5	55.5	52.8	52.1	51.6	52.2	45.2	44.5	34.3	35.0	32.9	46.5	47.2	46.5	46.9	35.6	37.4
mms	mean	126.85	126.46	126.20	126.46	135.19	133.91	134.03	125.95	125.69	125.31	125.43	111.70	111.70	110.41	110.03	102.46	120.43	119.91	120.17	120.43	109.64	109.00
	S.D.	15.15	15.28	15.40	15.34	17.34	17.63	17.60	15.26	15.37	15.51	15.47	13.23	13.21	9.33	9.49	9.44	13.16	13.49	13.35	13.23	10.30	10.51
channel 4	minimum	-0.9	-1.6	-1.6	-1.4	-1.0	-1.0	-1.4	-2.2	-1.8	-1.9	-1.4	-1.0	-0.6	-0.4	-0.3	-0.6	-0.5	-0.5	-0.5	-0.6	-1.5	-1.5
(actuator 2	maximum	6.6	3.6	4.1	3.7	6.2	4.6	4.6	5.6	4.9	4.3	4.7	2.6	1.9	4.3	3.2	1.6	5.5	4.2	3.6	3.5	4.9	3.8
- force)	mean	0.2	0.0	0.0	-0.1	0.2	0.1	0.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	0.3	0.1	0.1	0.3	0.1	0.1	0.1	0.0	0.1
Newtons	S.D.	0.85	0.46	0.51	0.45	0.77	0.57	0.60	0.93	0.71	0.64	0.66	0.29	0.22	0.94	0.63	0.32	1.14	0.82	0.69	0.66	0.94	0.78
	% data above mean	20.16	45.13	35.13	38.33	21.17	28.33	42.83	31.18	38.16	45.78	43.15	44.74	42.19	23.62	19.93	43.52	19.37	17.03	17.90	19.22	-	33.32

		45	46	47	48	49	50	51	52	53	54
	date	2/9/93		2/9/93				2/10/93		13/2/94	
	file name	SIN 58		SIN 60				SIN 64		SIN 71	
	minutes of data	45		45				39		34	
	period of cycles	2	3	2	3	4	5	1	2	1	2
channel 1	maximum	3.8	4.2	4.8	4.1	3.5	3.3	3.3	2.6	0.5	0.4
(actuator 1	minimum	-1.3	-2.4	-0.6	-0.7	-0.7	-0.6	-0.6	-0.6	-1.1	-0.9
- force)	mean	-0.1	-0.2	0.2	0.2	0.1	0.0	-0.1	-0.1	-0.4	-0.3
Newtons	S.D.	0.88	0.85	1.03	0.88	0.70	0.67	0.49	0.47	0.20	0.19
	% data above mean	77.81	73.03	76.60	75.62	74.86	72.78	76.40	70.27	51.48	49.32
channel 2	maximum	125.7	127.8	127.3	126.7	127.8	127.4	137.6	138.1	139.6	138.7
(actuator 2	minimum	85.9	85.8	86.4	86.4	86.8	86.8	97.5	96.3	97.7	98.2
- position)	range	39.8	42.0	40.9	40.3	41.0	40.7	40.2	41.8	41.9	40.5
mms	mean	105.73	105.48	105.98	105.73	105.98	105.73	116.15	115.90	115.02	115.77
	S.D.	11.05	11.32	10.83	11.08	11.01	11.03	11.34	11.49	10.56	10.60
channel 3	maximum	127.6	128.9	126.7	126.2	126.6	126.6	140.1	139.4	129.9	130.7
(actuator 1	minimum	89.7	89.5	89.9	89.7	89.6	89.6	98.5	98.1	97.3	97.8
- position)	range	37.9	39.4	36.8	36.5	37.0	37.0	41.6	41.3	32.6	32.9
mms	mean	108.36	108.36	108.36	108.36	108.49	108.23	119.02	118.89	116.32	117.22
	S.D.	11.13	11.29	10.87	10.94	10.94	10.99	11.68	11.75	9.11	8.92
channel 4	minimum	-0.4	-0.5	-1.0	-1.1	-1.0	-1.3	-0.5	-0.8	-1.3	-1.1
(actuator 2	maximum	6.7	5.4	4.1	3.9	3.9	3.8	1.9	1.5	0.6	0.5
- force)	mean	0.4	0.2	0.0	0.0	0.1	-0.1	0.1	-0.1	-0.1	-0.2
Newtons	S.D.	1.07	0.79	0.64	0.65	0.58	0.55	0.37	0.31	0.39	0.31
	% data above mean	19.66	19.38	39.30	33.65	46.13	41.19	44.27	43.92	52.95	47.35

		55	56	57	58	59	60	61	62	63	64
	date	16/2/94				16/2/94		17/2/94			
	file name	SIN 72				SIN 73		SIN 74			
	minutes of data	45				20		41			
	period of cycles	1	2	3	4	1	2	2	3	4	5
channel 1	maximum	1.7	1.2	0.8	0.6	5.9	4.1	2.1	1.6	1.1	1.2
(actuator 1	minimum	-1.7	-1.4	-2.3	-2.2	-6.2	-5.7	-2.4	-2.3	-1.9	-1.9
- force)	mean	-0.5	-0.5	-0.4	-0.4	-0.1	-0.1	-0.3	-0.4	-0.5	-0.4
Newtons	S.D.	0.40	0.30	0.25	0.26	1.33	1.00	0.33	0.36	0.38	0.33
	% data above mean	44.36	52.85	53.08	47.45	65.44	66.12	45.08	45.19	44.81	47.52
channel 2	maximum	133.1	131.6	132.7	132.5	113.8	114.0	145.0	143.6	145.5	144.3
(actuator 2	minimum	88.7	88.9	89.0	87.8	88.3	88.3	99.1	98.1	98.7	97.1
- position)	range	44.4	42.7	43.7	44.7	25.5	25.7	45.9	45.5	46.8	47.2
mms	mean	109.00	108.62	108.49	108.49	98.21	97.83	119.16	119.16	118.78	118.66
	S.D.	11.41	11.43	11.58	11.58	6.68	6.61	12.43	12.36	12.48	12.46
channel 3	maximum	128.4	128.3	128.4	127.7	110.2	109.8	139.3	139.8	138.8	138.8
(actuator 1	minimum	91.2	90.6	91.4	89.1	81.4	81.9	99.4	99.2	99.0	99.4
- position)	range	37.2	37.6	37.0	38.6	28.8	27.9	39.9	40.6	39.8	39.4
mms	mean	111.19	110.67	110.54	110.67	98.48	98.35	121.45	121.33	120.94	120.94
	S.D.	10.66	10.76	10.85	10.82	7.50	7.47	11.67	11.67	11.79	9.14
channel 4	minimum	-0.4	-0.7	-0.8	-0.4	-1.3	-2.5	-0.4	-0.2	-0.5	-0.3
(actuator 2	maximum	4.2	4.0	3.0	3.0	3.3	3.8	2.7	2.9	2.5	2.1
- force)	mean	0.4	0.3	0.3	0.3	0.8	0.8	0.4	0.4	0.3	0.2
Newtons	S.D.	0.80	0.68	0.52	0.51	0.92	0.80	0.51	0.47	0.46	0.34
	% data above mean	26.36	26.45	30.32	28.71	35.30	33.82	24.89	24.46	21.67	30.35

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patient #9 - GE

digs 2 & 4 PIP right

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	date	9/1/93		14/1/93						21/1/93						2/2/93				
	file name	ELY1		ELY9						ELY19						ELY41				
	minutes of data	7		45						44						46				
	period of cycles	1	2	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5
channel 1	maximum	0.0	0.4	1.3	4.8	1.5	1.0	1.1	2.5	0.1	0.6	0.6	0.4	-0.1	-0.1	-1.7	-0.8	-0.5	-0.4	-0.1
(actuator 1	minimum	-7.2	-5.5	-6.2	-5.9	-5.0	-4.4	-7.2	-5.3	-7.0	-5.8	-5.1	-5.0	-4.7	-4.9	-8.3	-5.1	-4.6	-4.2	-5.9
- force)	mean	-2.9	-2.1	-2.6	-1.8	-1.8	-1.9	-1.7	-2.0	-2.7	-2.3	-2.1	-1.6	-1.9	-1.8	-5.2	-3.5	-2.9	-2.7	-2.7
Newtons	S.D.	1.95	1.53	1.79	1.55	1.29	1.24	1.35	1.57	1.86	1.42	1.25	1.34	1.18	1.16	1.40	0.99	0.93	0.91	0.95
	% data above mean	51.24	47.58	50.31	44.94	48.44	50.99	46.86	48.88	44.62	45.33	46.16	41.92	43.23	41.76	54.26	60.69	59.80	63.56	53.70
channel 2	maximum	147.3	148.3	154.7	155.9	154.8	154.5	154.9	153.9	169.1	170.0	168.5	168.6	169.3	168.8	124.6	124.9	126.2	125.1	124.8
(actuator 2	minimum	104.7	104.5	92.3	91.4	92.1	91.7	91.6	92.1	124.3	125.1	123.6	123.8	123.4	123.7	104.5	104.4	104.2	104.1	104.0
- position)	range	42.5	43.8	62.4	64.5	62.7	62.9	63.4	61.9	44.8	44.9	44.9	44.8	45.9	45.2	20.1	20.6	22.0	21.0	20.8
mms	mean	123.17	123.05	119.28	119.66	119.91	119.79	119.54	119.54	146.76	146.51	146.64	146.51	146.39	146.14	113.39	113.01	113.26	113.14	113.01
	S.D.	12.40	12.65	17.50	17.78	17.92	17.84	17.74	17.78	12.16	12.30	12.37	12.28	12.25	12.14	5.68	5.47	5.60	5.60	5.51
channel 3	maximum	133.8	133.9	135.3	136.0	134.8	135.3	135.4	135.2	170.4	170.6	170.1	170.0	170.1	170.5	118.4	118.2	118.1	118.5	118.1
(actuator 1	minimum	101.2	101.3	90.5	90.4	90.4	89.4	88.8	89.6	140.7	127.7	126.2	126.6	126.2	127.2	104.0	103.6	104.5	104.4	104.0
- position)	range	32.6	32.6	44.8	45.6	44.4	46.0	46.6	45.6	29.7	42.9	43.9	43.4	43.9	43.3	14.4	14.6	13.6	14.1	14.1
mms	mean	122.48	122.22	118.37	118.63	118.89	118.76	118.50	118.63	150.34	150.08	150.08	150.08	149.95	149.95	113.24	113.24	113.24	113.24	113.24
	S.D.	9.17	9.32	13.52	13.63	13.58	13.58	13.58	13.61	12.22	12.34	12.41	12.36	12.31	12.30	3.22	3.18	3.18	3.22	3.23
channel 4	minimum	-6.6	-5.3	-8.2	-8.8	-9.2	-10.0	-8.7	-8.1	-5.2	-4.8	-4.2	-5.4	-4.1	-4.3	-7.2	-6.1	-5.7	-5.2	-6.0
(actuator 2	maximum	1.9	2.4	4.2	3.9	3.8	2.8	3.5	3.5	3.5	1.8	1.8	4.0	0.9	0.8	0.4	0.4	0.7	0.5	0.2
- force)	mean	-0.8	-0.4	-0.5	-0.9	-1.3	-2.2	-1.5	-0.6	-0.6	-0.7	-0.6	-0.4	-0.6	-0.6	-2.1	-1.6	-1.4	-1.3	-1.3
Newtons	S.D.	1.60	1.40	2.20	2.67	2.54	2.87	2.55	2.02	1.36	1.12	1.01	1.31	0.86	0.85	1.92	1.56	1.45	1.40	1.31
	% data above mean	72.53	64.53	59.50	59.36	57.59	57.46	56.06	60.17	60.61	66.08	64.29	61.51	62.41	63.93	63.73	62.89	64.42	63.95	63.64

		20	21	22	23	24	25	26	27	28
	date	2/2/93		2/3/93		2/4/93		2/12/96?		
	file name	ELY42		ELY48		ELY51		ELY56		
	minutes of data	17		24		20		24		
	period of cycles	1	2	1	2	1	2	1	2	3
channel 1	maximum	-0.4	-0.3	-0.2	0.0	-1.0	-0.3	-0.5	-0.2	-0.3
(actuator 1	minimum	-5.7	-3.8	-4.5	-3.1	-7.9	-7.1	-4.2	-3.8	-3.6
- force)	mean	-2.7	-2.0	-2.4	-1.7	-4.5	-3.5	2.9	-2.6	-2.4
Newtons	S.D.	1.07	0.87	1.13	0.84	1.54	1.52	0.86	0.82	0.71
	% data above mean	56.54	55.17	61.97	61.48	53.88	53.11	65.13	-	63.79
channel 2	maximum	134.8	135.1	137.7	138.5	122.4	121.9	117.2	115.8	117.4
(actuator 2	minimum	87.5	87.2	124.2	123.6	102.8	103.1	83.0	83.0	82.9
- position)	range	47.3	47.9	13.6	14.9	19.6	18.8	34.1	32.7	34.5
mms	mean	109.37	109.37	128.19	128.07	110.88	115.65	96.45	96.07	96.57
	S.D.	13.55	13.68	3.80	3.82	4.87	4.91	9.59	9.60	9.86
channel 3	maximum	105.5	105.4	127.4	127.9	120.0	-	95.4	94.5	95.0
(actuator 1	minimum	87.8	87.7	112.9	112.7	102.8	-	78.3	78.8	78.8
- position)	range	17.7	17.7	14.5	15.1	17.2	-	17.1	15.7	16.2
mms	mean	100.79	100.66	123.00	122.74	112.85	-	89.11	89.11	89.11
	S.D.	3.91	3.97	4.02	4.06	4.45	-	3.31	3.53	3.43
channel 4	minimum	-8.9	-8.0	-2.8	-3.0	-8.7	-	-7.1	-6.6	-6.5
(actuator 2	maximum	0.2	0.9	0.0	-0.1	0.0	-	0.5	0.4	0.4
- force)	mean	-2.0	-1.7	-1.0	-0.9	-3.0	-	-1.4	-1.1	-1.2
Newtons	S.D.	2.31	1.97	0.59	0.61	2.05	-	1.78	1.67	1.54
	% data above mean	65.97	66.61	66.40	67.28	60.41	-	66.76	69.15	67.47

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patient #10 - RV

dig 2 PIP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	date	06/02/93				09/02/93		10/02/93			11/02/93			13/02/93						
	file name	VAN1				VAN 3		VAN 6			VAN 7			VAN 9						
	minutes of data	32				20		42			22			58						
	period of cycles	1	2	3	4	1	2	1	first half	second half	1	2	3	1	2	3	4	5	6	7
channel 1	maximum	-	-	-	-	-	-	-	-	-	-	-	-	-0.1	-0.1	-0.1	0.0	0.0	-0.1	0.0
(actuator 1	minimum	-	-	-	-	-	-	-	-	-	-	-	-	-1.6	-1.5	-1.7	-1.8	-1.5	-1.5	-1.6
- force)	mean	-	-	-	-	-	-	-	-	-	-	-	-	-0.7	-0.7	-0.7	-0.8	-0.7	-0.7	-0.7
Newtons	S.D.	-	-	-	-	-	-	-	-	-	-	-	-	0.28	0.30	0.36	0.39	0.34	0.35	0.38
	% data above mean	-	-	-	-	-	-	-	-	-	-	-	-	44.44	-	-	46.76	44.15	47.80	42.01
channel 2	maximum	98.7	99.0	111.9	111.4	122.9	122.8	125.9	-	-	110.9	111.5	111.4	115.8	116.4	116.4	115.0	116.0	115.6	115.9
(actuator 2	minimum	79.1	79.5	80.5	80.6	84.7	85.4	86.0	-	-	84.7	84.9	84.9	82.6	82.5	82.3	82.3	82.4	82.3	82.4
- position)	range	19.6	19.4	31.4	30.7	38.3	37.4	39.9	-	-	26.2	26.6	26.5	33.1	33.9	34.1	32.7	33.6	33.4	33.5
mms	mean	88.29	88.54	94.82	94.82	105.86	105.98	107.62	-	-	97.20	97.33	97.20	99.08	98.96	99.08	98.96	98.96	99.08	99.08
	S.D.	5.59	5.53	8.89	8.96	11.39	11.36	11.60	-	-	7.37	7.47	7.54	8.41	8.24	8.25	8.33	8.33	8.30	8.44
channel 3	maximum	-	-	-	-	-	-	-	-	-	-	-	-	108.0	108.5	108.0	108.1	108.2	108.4	108.0
(actuator 1	minimum	-	-	-	-	-	-	-	-	-	-	-	-	96.7	97.2	97.1	96.6	96.6	96.7	96.6
- position)	range	-	-	-	-	-	-	-	-	-	-	-	-	11.3	11.3	10.9	11.6	11.7	11.7	11.4
mms	mean	-	-	-	-	-	-	-	-	-	-	-	-	102.20	102.07	102.07	101.94	102.07	102.20	102.20
	S.D.	-	-	-	-	-	-	-	-	-	-	-	-	2.85	2.80	278.43	2.87	2.88	2.87	2.83
channel 4	minimum	-6.1	-4.2	-3.6	-3.4	-3.2	-2.9	-4.9	-4.9	-4.3	-4.0	-3.7	-3.1	-5.2	-5.0	-4.2	-4.1	-4.1	-4.1	-3.7
(actuator 2	maximum	0.5	0.3	3.3	2.8	0.5	0.5	2.9	2.9	1.9	1.6	1.9	1.9	0.9	0.7	0.7	0.6	0.5	0.6	0.7
- force)	mean	-1.5	-1.0	0.1	0.0	-0.8	-0.7	-1.1	-1.1	-1.0	-0.8	-0.5	-0.4	-1.0	-1.0	-0.6	-0.6	-0.7	-0.6	-0.5
Newtons	S.D.	1.81	1.34	1.37	1.10	1.14	1.04	1.56	1.66	1.45	1.31	1.12	1.08	1.48	1.33	1.20	1.16	1.12	1.16	1.02
	% data above mean	59.27	65.08	55.66	58.42	65.23	65.17	-	62.07	63.71	58.36	56.52	63.49	64.55	65.69	67.82	70.03	70.27	71.33	69.41

		20	21	22	23	24
	date	16/02/93				
	file name	VAN 11				
	minutes of data	46				
	period of cycles	1	2	3	4	5
channel 1	maximum	-	-	-	-	-
(actuator 1	minimum	-	-	-	-	-
- force)	mean	-	-	-	-	-
Newtons	S.D.	-	-	-	-	-
	% data above mean	-	-	-	-	-
channel 2	maximum	159.4	157.9	156.9	157.7	157.8
(actuator 2	minimum	105.1	104.9	104.7	104.7	104.7
- position)	range	54.3	53.1	52.2	52.9	53.1
mms	mean	126.94	126.56	126.94	127.06	126.94
	S.D.	16.42	16.30	16.49	16.47	16.35
channel 3	maximum	-	-	-	-	-
(actuator 1	minimum	-	-	-	-	-
- position)	range	-	-	-	-	-
mms	mean	-	-	-	-	-
	S.D.	-	-	-	-	-
channel 4	minimum	-5.8	-5.4	-5.4	-6.8	-6.4
(actuator 2	maximum	0.5	0.4	0.8	0.6	0.5
- force)	mean	-1.1	-1.1	-1.0	-1.0	-1.1
Newtons	S.D.	1.71	1.71	1.64	1.57	1.75
	% data above mean	67.26	66.13	67.64	67.46	68.10

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patient #12 - EP

dig 5 PIP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	date	28/11/93						29/11/93						07/12/93				
	file name	PAJ 1						PAJ 2						PAJ 8				
	minutes of data	56						58						58				
	period of cycles	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5
channel 1	maximum	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	11.0	9.9	7.8	9.8	8.9
(actuator 1	minimum	-0.4	-0.3	-0.3	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-3.3	-3.4	-3.2	-2.8	-3.1
- force)	mean	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.1	0.4	0.2	0.2	0.3	0.3
Newtons	S.D.	0.101	0.103	0.100	0.100	0.094	0.098	0.079	0.084	0.085	0.081	0.088	0.086	2.300	1.867	1.645	1.780	1.762
	% data above mean	-	-	-	-	-	-	-	-	-	-	-	-	75.98	71.16	69.54	77.10	72.97
channel 2	maximum	158.8	158.9	160.2	160.9	158.8	160.2	144.3	144.3	145.1	144.3	144.4	145.8	123.4	123.0	123.4	123.0	123.4
(actuator 2	minimum	112.1	111.6	113.0	112.3	112.6	113.3	95.9	96.7	95.6	96.3	95.3	97.6	110.1	110.4	110.4	110.5	110.3
- position)	range	46.7	47.3	47.2	48.7	46.2	46.9	48.3	47.6	49.6	47.9	49.1	48.2	13.3	12.7	13.0	12.5	13.2
mms	mean	137.10	136.85	136.73	136.98	136.85	136.73	122.67	122.67	122.30	122.67	126.31	123.05	117.03	117.03	116.90	117.03	116.90
	S.D.	12.56	12.63	12.71	12.65	12.63	12.63	13.73	13.64	13.95	13.69	13.81	13.56	2.90	2.86	2.84	2.81	2.89
channel 3	maximum	157.0	157.7	158.2	157.8	157.0	156.9	148.7	149.6	150.3	148.9	149.6	150.6	153.2	152.1	152.6	154.4	154.8
(actuator 1	minimum	143.5	142.3	143.1	143.4	143.8	143.7	133.5	133.3	133.5	133.0	133.3	133.1	92.7	94.9	94.5	95.0	94.5
- position)	range	13.5	15.4	15.0	14.4	13.2	13.2	15.1	16.3	16.8	15.9	16.3	17.5	60.5	57.3	58.2	59.4	60.3
mms	mean	148.93	148.93	148.93	149.05	148.93	148.93	138.14	138.01	137.89	138.01	138.01	138.01	123.12	123.51	123.38	123.38	123.12
	S.D.	2.76	2.86	2.85	2.81	2.80	2.73	3.38	3.25	3.35	3.36	3.42	3.47	15.58	15.43	15.35	15.44	15.48
channel 4	minimum	-2.2	-1.9	-1.9	-2.0	-2.0	-2.3	-2.0	-2.0	-2.0	-1.9	-1.8	-1.9	-0.2	-	-	-	-
(actuator 2	maximum	7.2	5.4	5.1	6.1	6.0	5.9	5.7	5.8	5.3	3.6	5.3	5.3	0.3	-	-	-	-
- force)	mean	0.4	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2	-0.1	0.1	0.1	0.1	-	-	-	-
Newtons	S.D.	1.53	1.12	1.02	1.23	1.25	1.09	1.30	1.30	1.22	0.84	0.99	1.06	0.09	-	-	-	-
	% data above mean	25.20	28.39	27.88	26.29	26.56	30.26	33.48	30.77	32.70	52.34	37.26	38.38	-	-	-	-	-

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patient #13 - Ma

digs 2 & 5 PIP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	date	24/12/93				16/01/94				21/01/94					24/01/94				
	file name	MA 13				MA 46				MA 50					MA 55				
	minutes of data	55				56				54					65				
	period of cycles	1	2	3	4	1	2	3	4	1	2	3	4	5	1	2	3	4	5
channel 1	maximum	4.4	1.8	2.2	1.5	2.4	2.6	2.7	5.4	3.7	2.6	2.8	2.4	2.5	4.0	3.8	3.7	3.2	3.6
(actuator 1	minimum	-2.9	-2.5	-2.2	-1.8	-3.5	-2.7	-2.8	-2.4	-1.8	-1.4	-1.4	-1.6	-1.8	-1.6	-1.5	-1.2	-1.2	-1.3
- force)	mean	-0.4	-0.5	-0.3	-0.5	-0.7	-0.4	-0.4	0.2	-0.1	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.1	-0.1	0.0
Newtons	S.D.	0.97	0.77	0.77	0.70	1.25	0.96	0.94	1.18	0.97	0.75	0.74	0.68	0.69	0.91	0.84	0.80	0.75	0.75
	% data above mean	51.58	53.15	53.43	48.80	38.50	44.64	54.87	65.64	54.74	51.52	51.97	54.16	51.66	58.20	57.45	56.23	56.95	61.33
channel 2	maximum	155.9	155.7	155.7	156.4	159.8	160.1	160.8	161.1	154.9	154.4	153.9	154.8	154.5	156.3	158.6	156.5	157.4	156.9
(actuator 2	minimum	98.6	99.0	98.6	98.5	97.3	97.2	97.2	97.5	100.7	100.2	101.0	100.7	101.1	92.1	92.4	92.4	92.6	92.2
- position)	range	57.3	56.7	57.1	58.0	62.5	62.9	63.6	63.6	54.2	54.2	52.9	54.1	53.5	64.2	66.1	64.1	64.9	64.7
mms	mean	124.43	124.68	124.81	124.81	124.93	124.81	124.81	124.93	123.80	123.43	123.17	123.17	123.30	119.16	118.78	118.66	118.53	118.53
	S.D.	15.56	15.88	15.81	15.85	17.94	18.06	18.06	17.95	14.98	15.17	15.26	15.19	15.14	18.75	18.86	18.90	18.91	18.83
channel 3	maximum	146.9	146.7	146.9	147.3	151.1	151.1	151.1	151.2	141.5	141.0	141.2	141.0	141.0	131.3	131.3	131.3	131.5	131.2
(actuator 1	minimum	100.3	100.5	99.8	100.4	92.3	92.4	93.0	93.1	96.4	95.1	95.3	95.9	96.3	83.3	83.1	83.7	83.8	83.6
- position)	range	46.6	46.2	47.1	46.9	58.8	58.7	58.2	58.2	45.1	45.8	46.0	45.1	44.7	48.0	48.3	47.6	47.6	47.6
mms	mean	126.72	126.59	126.46	126.59	126.33	126.59	126.72	126.46	124.41	123.89	123.64	123.64	123.89	115.04	115.55	115.55	115.42	115.55
	S.D.	14.24	14.54	14.60	14.54	17.45	17.38	17.32	17.37	12.93	13.20	13.47	13.41	13.25	14.34	13.77	13.97	13.97	13.77
channel 4	minimum	-0.3	-1.4	-0.4	-0.2	-0.8	-0.8	-0.7	-0.9	-0.4	-0.4	-0.3	-0.6	-0.2	-0.1	0.1	-0.2	0.0	0.0
(actuator 2	maximum	7.7	5.1	5.4	4.4	2.1	2.7	2.2	7.2	5.5	3.7	3.4	2.8	2.9	3.2	3.1	3.1	3.0	2.8
- force)	mean	1.4	1.0	1.0	0.8	0.3	0.5	0.4	1.0	1.0	0.7	0.7	0.6	0.6	1.1	1.0	1.0	1.0	0.9
Newtons	S.D.	1.80	1.21	1.19	1.00	0.53	0.57	0.50	1.49	1.31	0.92	0.84	0.77	0.69	0.77	0.72	0.71	0.62	0.61
	% data above mean	31.43	32.44	30.33	29.91	30.34	29.27	34.46	27.95	30.80	28.58	28.99	27.86	30.45	31.89	33.47	30.33	36.51	31.71

		19	20	21	22	23	24	25	26	27	28	29	30	31
	date	24/01/94						28/01/94					28/01/94	
	file name	MA 56						MA 57					MA 58	
	minutes of data	65						53					24	
	period of cycles	1	2	3	4	5	6	1	2	3	4	5	1	2
channel 1	maximum	4.1	3.9	3.4	4.1	3.6	4.2	2.6	2.6	1.8	2.2	1.6	2.3	2.1
(actuator 1	minimum	-2.0	-1.1	-1.1	-0.9	-0.9	-2.0	-2.0	-2.4	-1.9	-2.0	-2.0	-1.4	-1.2
- force)	mean	0.2	0.2	0.1	0.2	0.2	0.2	-0.4	-0.6	-0.4	-0.4	-0.4	-0.2	-0.2
Newtons	S.D.	0.78	0.81	0.73	0.76	0.74	0.76	0.95	0.88	0.79	0.83	0.77	0.76	0.79
	% data above mean	53.11	57.92	56.80	59.31	59.33	54.07	50.20	48.15	49.84	47.36	46.22	54.32	51.98
channel 2	maximum	124.3	124.8	124.4	124.6	124.6	124.9	154.0	154.4	154.3	155.2	154.5	139.6	139.7
(actuator 2	minimum	87.7	88.0	87.9	87.7	87.5	88.0	89.0	89.3	88.9	88.4	88.5	96.6	96.6
- position)	range	36.6	36.8	36.5	36.9	37.0	36.9	65.0	65.1	65.4	66.8	66.0	43.0	43.2
mms	mean	103.10	102.85	102.85	102.97	102.97	102.72	118.66	118.41	118.41	118.16	118.16	113.51	113.76
	S.D.	10.25	10.31	10.29	10.27	10.27	10.37	17.97	18.13	18.07	18.21	18.19	12.25	12.30
channel 3	maximum	124.5	124.2	123.3	123.5	123.8	124.0	136.6	136.7	136.5	136.9	137.0	131.5	131.9
(actuator 1	minimum	80.2	80.5	79.2	79.2	79.1	80.4	88.6	89.6	89.7	89.5	89.2	86.8	86.3
- position)	range	44.3	43.6	44.0	44.3	44.7	43.6	48.0	47.1	46.7	47.4	47.8	44.7	45.6
mms	mean	104.64	104.38	104.25	104.38	104.51	104.12	118.76	118.37	118.37	118.37	118.25	114.14	114.14
	S.D.	11.78	11.86	11.92	11.83	11.82	12.02	14.25	14.58	14.44	14.51	14.62	12.70	12.66
channel 4	minimum	-0.3	-0.3	-0.3	-0.3	-0.3	-0.8	0.0	0.0	0.1	0.1	0.1	-0.7	-0.5
(actuator 2	maximum	6.3	5.0	6.1	5.0	4.6	3.5	6.1	3.9	3.6	3.6	3.2	3.3	3.4
- force)	mean	1.8	1.4	1.4	1.3	1.2	1.3	1.3	1.0	1.0	1.0	0.9	0.9	0.9
Newtons	S.D.	1.52	1.17	1.14	1.19	1.01	1.17	1.21	0.78	0.71	0.74	0.59	0.76	0.72
	% data above mean	36.65	35.06	34.42	30.71	32.62	32.96	28.53	25.75	28.00	26.12	26.40	37.70	34.82

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patient #14 - H

digs 2 & 3 PIP left

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	date	01/04/94	23/08/94						01/10/94					01/10/94			
	file name	HA1	HAR4N						HAR8					HAR9			
	minutes of data	27	58						56					46			
	period of cycles	1	1	2	3	4	5	6	1	2	3	4	5	1	2	4	5
channel 1	maximum	5.9	3.0	2.3	2.2	1.9	1.7	1.6	14.7	12.4	13.5	12.0	11.4	1.7	1.8	1.5	0.4
(actuator 1	minimum	-6.7	-2.4	-1.2	-1.7	-1.3	-1.8	-2.1	-3.8	-5.5	-3.8	-5.1	-9.8	-4.3	-3.6	-6.8	-4.5
- force)	mean	-0.2	0.2	0.1	-0.1	-0.2	-0.3	-0.1	0.8	0.3	1.1	0.5	0.5	-1.2	-1.7	-1.6	-1.7
Newtons	S.D.	1.06	0.63	0.52	0.64	0.49	0.57	0.54	3.93	3.38	3.50	3.49	3.34	1.16	1.80	1.11	1.71
	% data above mean	68.40	60.64	58.21	46.00	57.39	47.81	50.67	69.87	68.63	64.81	59.91	59.57	39.31	37.47	39.62	30.89
channel 2	maximum	162.9	165.3	166.3	166.3	165.3	166.0	166.8	157.9	160.1	160.1	159.4	159.1	167.1	167.0	167.0	168.8
(actuator 2	minimum	80.4	109.2	109.5	109.6	109.1	109.5	109.5	82.0	81.4	82.5	81.0	80.1	107.6	107.4	107.1	107.7
- position)	range	82.6	56.1	56.8	56.7	56.2	56.5	57.3	75.9	78.7	77.5	78.4	78.9	59.5	59.6	59.8	61.1
mms	mean	121.29	134.47	133.59	133.59	133.46	133.71	133.84	120.92	121.54	121.29	120.92	120.79	135.22	135.22	135.47	136.35
	S.D.	20.97	16.91	17.01	17.00	17.06	17.08	17.04	22.50	22.18	22.37	22.48	22.67	16.74	16.91	16.93	16.68
channel 3	maximum	167.0	167.7	167.9	168.1	167.3	168.4	168.2	166.9	168.4	168.7	169.5	167.7	168.7	169.0	169.0	169.9
(actuator 1	minimum	82.6	95.9	96.3	95.1	94.5	95.4	95.0	85.4	83.7	85.0	84.1	83.2	106.2	105.4	104.9	105.7
- position)	range	84.5	71.8	71.6	72.9	72.8	73.0	73.2	81.5	84.7	83.7	85.4	84.5	62.5	63.5	64.1	64.2
mms	mean	124.41	136.35	135.32	135.70	135.45	134.93	135.32	123.89	124.41	124.41	124.66	124.15	138.53	139.17	138.53	139.68
	S.D.	21.45	19.41	19.67	19.41	19.61	20.04	19.77	23.40	23.25	23.23	23.09	23.41	17.51	17.30	17.74	17.43
channel 4	minimum	-1.8	0.3	0.3	0.2	0.2	0.1	-0.2	-1.5	-2.1	-1.2	-1.6	-2.3	-2.8	-1.8	-1.3	-1.7
(actuator 2	maximum	7.7	5.7	3.4	3.5	3.3	3.2	2.4	13.7	11.7	10.6	10.8	8.8	8.3	7.8	6.7	5.1
- force)	mean	0.2	1.7	1.2	1.1	1.1	1.0	0.9	0.9	0.4	0.7	0.7	0.6	0.2	0.6	0.5	0.2
Newtons	S.D.	1.35	1.22	0.79	0.66	0.65	0.62	0.52	2.70	2.21	2.03	2.15	1.84	1.79	1.95	1.58	1.22
	% data above mean	25.73	36.74	36.32	37.60	35.19	35.05	37.96	26.08	25.26	26.78	25.74	27.39	28.95	23.73	24.28	22.36

		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	date	01/11/94					16/01/94				16/01/94			17/01/94					17/01/94
	file name	HAR10					HAR16				HAR17			HAR18					HAR19
	minutes of data	61					54				32			56					46
	period of cycles	1	2	3	4	5	1	3	4	5	1	2	3	2	3	4	5	6	1
channel 1	maximum	10.5	8.9	9.0	7.2	7.5	5.7	6.7	7.5	6.8	5.0	5.8	5.7	6.8	5.9	4.1	4.5	4.1	2.9
(actuator 1	minimum	-3.2	-2.0	-3.1	-4.5	-4.5	-9.8	-5.5	-3.0	-4.0	-3.2	-7.2	-6.2	-3.3	-3.5	-3.2	-2.6	-3.1	0.3
- force)	mean	0.4	1.1	1.2	0.8	1.1	-2.2	0.1	0.1	-0.1	-0.9	-1.3	-1.0	-0.1	-0.2	-0.6	-0.1	-0.4	1.6
Newtons	S.D.	2.19	1.99	2.03	1.90	1.76	2.73	2.11	2.24	2.11	1.38	1.69	1.60	2.03	1.79	1.77	1.36	1.59	0.22
	% data above mean	63.54	63.33	62.02	57.57	62.15	47.88	56.97	54.72	55.88	57.95	61.56	59.18	62.02	57.78	48.07	56.88	51.32	45.53
channel 2	maximum	117.9	117.2	117.4	117.2	117.0	140.6	140.6	140.5	140.4	166.1	166.0	166.7	166.6	166.6	167.5	166.1	165.7	
(actuator 2	minimum	79.0	79.6	78.8	78.8	78.6	80.0	80.5	81.1	80.8	129.1	128.7	128.7	80.8	80.6	80.8	81.0	81.0	
- position)	range	38.9	37.5	38.6	38.4	38.4	60.6	60.1	59.3	59.6	37.0	37.3	38.0	85.8	85.9	86.7	85.1	84.7	
mms	mean	98.21	98.08	98.08	98.21	98.21	114.01	112.63	112.89	111.63	139.49	139.86	139.86	124.18	124.30	124.81	124.81	124.68	
	S.D.	10.86	10.92	10.98	10.98	10.87	17.50	18.12	17.93	18.63	10.91	11.02	11.02	23.71	23.68	23.30	23.43	23.48	
channel 3	maximum	124.9	124.7	123.1	123.9	124.3	152.6	152.6	152.3	153.3	165.4	165.1	165.1	168.2	167.3	167.7	168.2	167.9	
(actuator 1	minimum	79.1	80.1	79.7	79.3	79.2	83.2	83.7	84.0	83.3	84.9	84.6	85.3	92.2	92.4	93.0	92.4	92.4	
- position)	range	45.8	44.5	43.4	44.5	45.1	69.4	68.9	68.3	70.0	80.5	80.5	79.8	76.0	74.8	74.7	75.7	75.5	
mms	mean	100.92	100.92	100.79	101.04	101.04	117.48	116.06	116.06	115.93	130.06	131.60	131.34	128.00	127.87	128.26	128.13	128.13	
	S.D.	11.56	11.65	11.71	11.66	11.52	18.65	19.23	19.17	19.32	24.11	23.43	23.66	23.20	23.29	23.09	23.22	23.18	
channel 4	minimum	-1.7	-0.4	-0.3	-0.7	-0.9	-3.2	-1.3	-1.2	-1.0	-1.1	-1.8	-2.0	-2.1	-2.1	-2.0	-1.6	-2.0	0.0
(actuator 2	maximum	3.4	3.5	4.2	3.5	4.2	3.3	3.5	3.7	3.3	7.7	8.5	12.7	6.2	5.2	5.3	5.3	4.8	3.9
- force)	mean	0.3	0.6	0.7	0.7	0.7	-0.8	0.1	0.1	0.0	2.5	2.6	2.3	-0.1	-0.1	-0.1	0.0	0.0	1.6
Newtons	S.D.	0.73	0.88	0.90	0.89	0.90	0.94	0.68	0.64	0.66	2.90	2.58	2.32	0.95	0.91	0.90	0.74	0.90	0.58
	% data above mean	36.05	33.74	34.27	31.49	34.12	52.72	36.68	35.84	37.48	55.19	52.98	52.86	31.37	30.02	43.54	34.61	37.00	41.58

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